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BADANIE ODPORNOŚCI PROCESÓW TRANSPORTOWYCH NA ZAKŁÓCENIA WSPÓŁCZESNYCH KRYZYSÓW

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SPIS TREŚCI

STRESZCZENIE W JĘZYKU POLSKIM

BADANIE ODPORNOŚCI PROCESÓW TRANSPORTOWYCH NA ZAKŁÓCENIA WSPÓŁCZESNYCH KRYZYSÓW

Współczesna gospodarka funkcjonuje w warunkach nasilających się zakłóceń o wieloaspektowej genezie, których oddziaływanie w istotny sposób obejmuje także sektor transportu. Na jego funkcjonowanie wpływają zarówno kryzysy nagłe, w tym zdrowotne i militarne, jak i długookresowe wyzwania środowiskowe, gospodarcze oraz społeczne. Zjawiska te prowadzą do zmian poziomu przewozów, ograniczeń mobilności oraz wzrostu presji adaptacyjnej w obszarze organizacji i rozwoju transportu. Przewidywana trwałość tych zjawisk w perspektywie długookresowej uzasadnia podejmowanie badań na poziomie poszczególnych procesów transportowych. Dlatego za cel pracy przyjęto zbadanie oddziaływania zróżnicowanych kryzysów na funkcjonowanie procesów transportowych, zidentyfikowanie mechanizmów oddziaływania zakłóceń oraz wzorców ryzyka z zastosowaniem metod matematycznych, a także opracowanie rekomendacji wspierających sektor transportu w warunkach niepewności.

Do analizy i oceny funkcjonowania procesów transportowych wykorzystano metody i modele matematyczne, w tym modele szeregów czasowych, modele ekonometryczne oraz algorytmy uczenia maszynowego, oparte na danych statystycznych, dotyczących polskiego systemu transportowego. Postępowanie badawcze obejmowało opracowanie typologii współczesnych kryzysów powiązanych z transportem oraz modelowanie istniejących zależności i wpływu wybranych czynników na zachodzące zmiany. W rezultacie wykazano zróżnicowane oddziaływanie poszczególnych kryzysów na funkcjonowanie procesów transportowych. Potwierdzono istnienie stabilnych, długookresowych zależności pomiędzy zmiennymi środowiskowymi i ekonomicznymi kształtującymi sektor transportu. Zidentyfikowano spadek liczby przewożonych pasażerów oraz zaburzenia dynamiki popytu na przewozy w warunkach kryzysu zdrowotnego. Ponadto stwierdzono zmiany wskaźników realizacji procesów transportowych w publicznym transporcie zbiorowym pod wpływem kryzysu militarnego oraz wykryto powtarzalne wzorce ryzyka i czynniki kształtujące bezpieczeństwo ruchu drogowego w Polsce. Na podstawie uzyskanych wyników opracowano rekomendacje i propozycje rozwiązań, które mogą znaleźć praktyczne zastosowanie w sferze gospodarczej i społecznej, zwłaszcza w obliczu współczesnych wyzwań i przyszłych kryzysów.

Słowa kluczowe: procesy transportowe, kryzysy związane z transportem, modelowanie matematyczne, analiza szeregów czasowych, odporność systemów transportowych, zarządzanie ryzykiem

STRESZCZENIE W JĘZYKU ANGIELSKIM

INVESTIGATION INTO THE RESILIENCE OF TRANSPORT PROCESSES TO CONTEMPORARY CRISIS DISRUPTIONS

The contemporary economy operates under conditions of intensifying disruptions of multifaceted origins, the effects of which significantly extend to the transport sector. Its functioning is influenced both by sudden crises, including health-related and military ones, and by long-term environmental, economic, and social challenges. These phenomena lead to changes in transport volumes, restrictions on mobility, and increased adaptive pressure in the organization and development of transport. The anticipated persistence of these phenomena in the long term justifies the undertaking of research at the level of individual transport processes. Therefore, the aim of this dissertation was to examine the impact of diverse crises on the functioning of transport processes, to identify the mechanisms through which disruptions affect them, as well as patterns of risk using mathematical methods, and to develop recommendations supporting the transport sector under conditions of uncertainty.

Methods and mathematical models were used to analyse and assess the functioning of transport processes, including time series models, econometric models, and machine learning algorithms based on statistical data concerning the Polish transport system. The research procedure included the development of a typology of contemporary crises related to transport, as well as the modeling of existing relationships and the impact of selected factors on ongoing changes. As a result, the differentiated impact of individual crises on the functioning of transport processes was demonstrated, and the existence of stable long-term relationships between environmental and economic variables shaping the transport sector was confirmed. A decline in the number of passengers transported and disruptions in the dynamics of transport demand under conditions of a health crisis were also identified. Moreover, changes in the performance indicators of transport processes in public collective transport under the influence of a military crisis were found, and recurring risk patterns as well as factors shaping road safety in Poland were detected. Based on the obtained results, recommendations and proposed solutions were developed that may find practical application in the economic and social spheres, especially in the face of contemporary challenges and future crises.

Keywords*:* transport processes, transport-related crises, mathematical modelling, time series analysis, transport system resilience, risk management

WYKAZ UŻYTYCH SKRÓTÓW

ACF – *ang. autocorrelation function*, funkcja autokorelacji

ADF – ang. *augmented Dickey–Fuller test*, rozszerzony test Dickeya-Fullera

AI – *ang. artificial intelligence*, sztuczna inteligencja

AIC – *ang. Akaike information criterion*, kryterium informacyjne Akaikego

ARIMA – *ang. autoregressive integrated moving average,* autoregresyjny zintegrowany model średniej ruchomej

BEV – *ang. battery electric vehicle,* pojazd w pełni elektryczny

BIC – *ang. Bayesian information criterion*, Bayesowskie kryterium informacyjne

CAGR – *ang. compound annual growth rate,* skumulowany roczny wskaźnik wzrostu

CPK – Centralny Port Komunikacyjny

EU ETS – *ang. European Union Emissions Trading System,* Europejski System Handlu Emisjami

FPE – *ang. Akaike's final prediction error,* kryterium ostatecznego błędu predykcji

HQC – *ang. Hannan–Quinn information criterion*, kryterium informacyjne Hannana-Quinna

IRF – *ang. impulse response function,* funkcja odpowiedzi impulsowej

KNN – *ang. K-Nearest Neighbors*, k-najbliższych sąsiadów

KPSS – test Kwiatkowskiego-Phillipsa-Schmidta-Shina

LOESS – *ang. locally estimated scatterplot smoothing*, lokalna regresja wygładzająca

MAE – *ang. Mean Absolute Error*, średni błąd bezwzględny

MAPE – *ang. Mean Absolute Percentage Error*, średni bezwzględny błąd procentowy

ME – *ang. Mean Error,* średni błąd

ML – *ang. machine learning*, uczenie maszynowe

OZE – odnawialne źródła energii

PHEV – *ang. plug-in hybrid vehicle,* pojazd hybrydowy typu plug-in

PP – test Phillipsa-Perrona

RF – *ang. Random Forest,* las losowy

RMSE – *ang. Root Mean Square Error*, pierwiastek z błędu średniokwadratowego

RPart – *ang. Recursive Partitioning and Regression Trees*, partycjonowanie rekurencyjne i drzewa regresyjne

SARIMA – *ang. seasonal autoregressive integrated moving average*, sezonowy autoregresyjny zintegrowany model średniej ruchomej

SC – *ang. Schwarz information criterion*, kryterium informacyjne Schwarza

STL – *ang. Seasonal-Trend decomposition using LOESS,* dekompozycja sezonowo-trendowa z wykorzystaniem LOESS

UE – *ang. European Union*, Unia Europejska

VAR – *ang. vector autoregression model*, model wektorowej autoregresji

VECM – *ang. vector error correction model*, model wektorowej korekty błędu

VFR – *ang. visiting friends and relatives*, odwiedzanie przyjaciół i krewnych

WHO – *ang. World Health Organization*, Światowa Organizacja Zdrowia

1. WPROWADZENIE

W ostatnich dekadach obserwuje się narastającą zmienność i niepewność procesów społeczno-gospodarczych zachodzących w skali światowej, co wynika z nakładania się wielu czynników o odmiennym charakterze i prowadzi do częstszego występowania zagrożeń o zasięgu ponadregionalnym i globalnym. Ponadto XXI wiek wyróżnia się dynamicznym rozwojem technologii, pogłębiającą się globalizacją gospodarki oraz intensyfikacją współpracy międzynarodowej [1], a zarazem występowaniem licznych kryzysów istotnie oddziałujących na funkcjonowanie gospodarki i społeczeństwa [2, 3]. Wyraźnie zaznaczyły się zdarzenia takie jak: globalny kryzys finansowy lat 2008–2009, destabilizujący międzynarodowe rynki kapitałowe i wymianę handlową [4]; nasilone przepływy migracyjne w drugiej dekadzie XXI wieku [5]; pandemia COVID-19 powodująca najgłębsze od powojennego okresu załamanie aktywności gospodarczej i bezprecedensowe ograniczenia mobilności [6, 7]; konflikty zbrojne o rozproszonym charakterze, zaburzające funkcjonowanie rynków surowcowych i łańcuchów dostaw [8, 9]. Doświadczenia te unaoczniły skalę podatności światowej gospodarki na zakłócenia oraz złożoność mechanizmów ich oddziaływania, dostrzegalnych również na poziomach krajowych [10]. Jednocześnie postępująca degradacja środowiska oraz zaburzenia klimatu [11, 12], prowadzące do narastającej presji regulacyjnej i przyspieszenia transformacji energetycznej [13, 14], w tym dekarbonizacji sektorów o wysokiej energochłonności [15] powodują, że kryzysy coraz częściej mają charakter wielowymiarowy i długotrwały.

W takich uwarunkowaniach szczególnego znaczenia nabiera transport, ponieważ od jego sprawnego funkcjonowania zależy zdolność gospodarki do stabilizacji oraz odbudowy po wystąpieniu zakłóceń. Sektor ten zapewnia ciągłość łańcuchów dostaw oraz mobilność ludności, a zarazem stanowi istotny element struktury ekonomicznej [16]. W Unii Europejskiej generuje około 5% produktu krajowego brutto oraz zatrudnia ponad 10 mln osób [17], będąc największym odbiorcą energii końcowej spośród wszystkich sektorów gospodarki (ok. 32%) [18]. Jednocześnie wysoka kapitałochłonność infrastruktury [19], zależność od uwarunkowań energetycznych [20] oraz silne powiązanie z poziomem popytu sprawiają, że transport należy do obszarów szczególnie wrażliwych na zmiany w otoczeniu [21]. Zjawiska kryzysowe mogą zatem bezpośrednio wpływać na organizację i poziom realizowanych przewozów, a także na ciągłość świadczonych usług – zarówno w skali międzynarodowej, jak i krajowej [22, 23].

Badania wskazują, że w przypadku zjawisk przebiegających w dłuższym horyzoncie czasowym, wynikających z uwarunkowań systemowych, wpływ na transport ujawnia się stopniowo poprzez zmiany kosztów, presję regulacyjną oraz długookresowe modyfikacje wzorców popytowych i organizacji funkcjonowania sektora. Do tej grupy należą głównie wyzwania związane z wysokim zużyciem energii oraz emisyjnością transportu [24]. W UE sektor ten odpowiada za blisko 25% całkowitych emisji gazów cieplarnianych [25], wciąż pozostając silnie uzależnionym od paliw kopalnych [26, 27], co w warunkach realizacji przyjętych celów klimatycznych, w tym pakietu „Fit for 55" [28, 29], generuje długookresową presję dostosowawczą wymagającą zmian technologicznych i inwestycyjnych [30–32]. Równolegle transport pozostaje obciążony innymi trwałymi wyzwaniami, w tym w obszarze bezpieczeństwa ruchu drogowego, gdzie pomimo obserwowanych trendów spadkowych liczby wypadków i ofiar, nadal generowane są istotne koszty społeczne i ekonomiczne [33, 34].

Odmienny charakter mają zdarzenia nagłe, które w krótkim czasie prowadzą do gwałtownych i znaczących zakłóceń. Przykładem jest wybuch pandemii COVID-19, któremu towarzyszyło wprowadzenie restrykcji sanitarnych, ograniczeń w przemieszczaniu oraz czasowych barier w ruchu międzynarodowym [35]. Poskutkowało to znaczącym spadkiem mobilności na świecie [36]. W 2020 r. liczba pasażerów w lotnictwie w ujęciu globalnym spadła o ok. 60% w porównaniu z rokiem poprzednim [37], a w wielu aglomeracjach świata ruch pasażerski w zbiorowym transporcie publicznym uległ znacznemu ograniczeniu [38, 39]. Istotne zmiany w mobilności można było zaobserwować również w kontekście zdarzeń o podłożu militarnym. Po wybuchu wojny na Ukrainie w 2022 r. napływ ludności do Europy Środkowej, w tym także do Polski, przełożył się na wzrost liczby przewozów, szczególnie w początkowej fazie konfliktu [40, 41]. Spowodowało to nagłą modyfikację otoczenia regulacyjno-popytowego, skutkując zaburzeniami poziomu i struktury przewozów oraz koniecznością szybkiego dostosowania organizacyjnego transportu do nowych warunków.

Mając na względzie powyższe rozważania dotyczące zróżnicowanego charakteru współczesnych kryzysów, system transportowy można traktować nie jako jednorodny obiekt badawczy, lecz jako zbiór procesów, które różnią się wrażliwością na zakłócenia oraz posiadają odmienne mechanizmy adaptacji [42, 43]. Procesy związane z długookresowymi trendami gospodarczymi i środowiskowymi charakteryzują się względną stabilnością oraz stopniowym dostosowywaniem do ewoluującego otoczenia. Z kolei pod wpływem zdarzeń nagłych mogą ulegać głębokim, często krótkookresowym zaburzeniom, po których następuje odbudowa lub trwała zmiana strukturalna [44, 45]. Istniejące zróżnicowanie utrudnia formułowanie wniosków dotyczących oddziaływania współczesnych kryzysów na transport traktowany jako całość. Zasadne staje się zatem prowadzenie badań na poziomie poszczególnych gałęzi transportu i zakłóceń. Wówczas procesy transportowe rozumiane są jako mierzalne zjawiska, których przebieg może być opisywany za pomocą odpowiednich zmiennych ilościowych.

Ich analiza wymaga uwzględnienia odmiennych horyzontów czasowych oraz specyfiki poszczególnych typów kryzysów [46]. Ujęcie to umożliwia precyzyjne badanie oddziaływania zjawisk kryzysowych na procesy transportowe, analizowanie zachodzących w nich zmian i istniejących zależności oraz ocenę skutków, co przyczynia się do lepszego rozpoznania uwarunkowań funkcjonowania sektora transportu w obliczu zakłóceń.

Jednocześnie kwerenda literatury wskazuje, że badanie procesów transportowych w kontekście kryzysów wiąże się z istotnymi wyzwaniami metodologicznymi, wynikającymi z ich złożoności i różnorodnej dynamiki rozwoju [47–49]. Odmienny zakres czasowy oddziaływania kryzysów oraz współwystępowanie wielu czynników wpływających na funkcjonowanie transportu wymaga zastosowania właściwych metod umożliwiających analizę trendów i fluktuacji czasowych [40, 50]. W tym kontekście znaczenia nabiera wykorzystanie metod matematycznych, pozwalających na modelowanie procesów transportowych w warunkach niepewności [51]. Poprawnie dobrany i skonstruowany model matematyczny, opisujący dany proces umożliwia nie tylko analizę zjawiska, ale także formułowanie wniosków o charakterze praktycznym, co ma szczególne znaczenie w sytuacji zakłóceń.

Istotną rolę modelowania matematycznego w badaniach dotyczących funkcjonowania transportu podkreślają liczne opracowania naukowe. Przegląd literatury potwierdza, że w ostatnich latach zauważalny jest wyraźny wzrost zainteresowania modelowaniem procesów transportowych obejmujący zarówno klasyczne modele szeregów czasowych, modele ekonometryczne, a także bardziej zaawansowane rozwiązania oparte na algorytmach uczenia maszynowego (*ang. machine learning*). Na przykład w [52], do prognozowania wolumenu ładunków kolejowych oraz oceny wpływu pandemii COVID-19 na poziom przewozów i uzyskiwane przychody zastosowano sezonowy model ARIMA. W innym badaniu wygładzanie wykładnicze Holta–Wintersa wykorzystano do oszacowania strat w pasażerskim transporcie lotniczym w Polsce i Niemczech podczas pandemii (2021–2022), poprzez porównanie prognoz z danymi rzeczywistymi [53]. Poza tym w analizach współzależności między zmiennymi ekonomicznymi i transportowymi szeroko stosowane są modele wektorowe. Model VAR wykorzystano do zbadania wpływu cen paliw, wzrostu gospodarczego i inflacji na wolumen przeładunków w polskich portach morskich [54], a także do oceny wpływu inwestycji w partnerstwa publiczno-prywatne w sektorze transportu na emisje CO_2 z transportu w regionie Azji Wschodniej i Pacyfiku [55]. Model VECM pozwolił na analizę długookresowych zależności i relacji przyczynowych między transportem towarowym, zużyciem energii, wzrostem gospodarczym oraz emisjami gazów cieplarnianych [56]. Z kolei uczenie maszynowe jest wykorzystywane najczęściej w odniesieniu do dużych zbiorów danych. Przykładowo w [57] omówiono zastosowanie złożonych algorytmów do analizy charakterystyk zdarzeń drogowych wskazując, że umożliwiają one predykcję poziomu ryzyka, częstości oraz ciężkości wypadków, wspierając tym samym działania na rzecz poprawy bezpieczeństwa ruchu drogowego. Inne obszary zastosowań ML obejmują prognozowanie popytu na przewozy towarowe oraz wspomaganie planowania operacji logistycznych [58], a także mapowanie emisji gazów z transportu drogowego, z wykorzystaniem modeli Random Forest opartych na danych o natężeniu ruchu [59].

Jak pokazano na przykładach, modelowanie matematyczne stosuje się w odniesieniu do wielu różnych obszarów transportu, jednak zakres prowadzonych analiz koncentruje się zazwyczaj na wybranym aspekcie jego funkcjonowania bądź określonym typie zakłócenia. Oznacza to, że chociaż istniejąca literatura dostarcza wielu pogłębionych badań, to najczęściej odnoszą się one do wąskiego zakresu zjawisk (np. danego podsystemu transportowego), analizowanych przy użyciu modeli matematycznych dobranych do specyfiki konkretnego problemu. Znacznie rzadziej podejmowane są natomiast rozważania naukowe, w ramach których różne typy współczesnych kryzysów rozpatrywane byłyby łącznie, w odniesieniu do określonych procesów transportowych, przy zachowaniu spójnej perspektywy badawczej i porównywalnych założeń. W rezultacie stan wiedzy na temat oddziaływań występujących w ostatnich latach zakłóceń rozwija się w sposób rozproszony, a możliwość syntetycznego ujęcia funkcjonowania transportu w odmiennych warunkach wciąż pozostaje ograniczona.

Należy również podkreślić, że zjawiska takie jak emisyjność transportu, jego podatność na załamania gospodarcze oraz zagrożenia zdrowotne, a także utrzymująca się skala i ciężkość wypadków drogowych, stanowią realne uwarunkowania, które w istotny sposób determinują funkcjonowanie i perspektywy rozwoju tego sektora [46, 60, 61]. Oddziaływanie to przekłada się zarówno na strukturę popytu i poziom przewozów, jak i na politykę inwestycyjną, interwencje regulacyjne oraz strategie działania podmiotów sektora transportu [62–64]. Dlatego znaczenia nabiera analiza i ocena oddziaływania różnych typów kryzysów na procesy transportowe, obejmująca identyfikację zmian i zależności zachodzących pod wpływem czynników o odmiennej genezie oraz ich konsekwencji dla całego sektora. Oznacza to konieczność badania sposobu, w jaki procesy te reagują na zakłócenia, jak kształtuje się ich dynamika w różnych horyzontach czasowych, a także jakie powiązania ujawniają się pomiędzy czynnikami, które na niego wpływają. W takim ujęciu odporność nie sprowadza się do braku wahań ani do powrotu do stanu sprzed kryzysu, lecz oznacza zdolność sektora transportu do adaptacji i utrzymania względnej stabilności w zmieniających się uwarunkowaniach, której przejawy mogą być identyfikowane w oparciu o dane liczbowe opisujące procesy.

Całościowe uwzględnienie powyższych rozważań pozwala stwierdzić, że podjęcie badań nad ilościową analizą i oceną funkcjonowania procesów transportowych w obliczu współczesnych kryzysów stanowi istotny krok w kierunku pogłębionego rozpoznania oddziaływania zakłóceń kryzysowych, sposobu reakcji na rzeczywiste wyzwania, a także uwarunkowań sektora transportu w zakresie odporności. Integracja analiz odnoszących się do odmiennych typów kryzysów, zróżnicowanych procesów transportowych, przy zastosowaniu adekwatnie dobranych modeli matematycznych, pozwala uchwycić złożoność zjawisk kształtujących transport, bez redukowania ich do fragmentarycznej interpretacji. Wyniki modelowania matematycznego nie ograniczają się wyłącznie do rozpoznania zależności i zakłóceń, lecz stanowią solidną podstawę do formułowania rekomendacji oraz propozycji rozwiązań ukierunkowanych na wzmacnianie odporności sektora transportu. Wypracowane w ten sposób praktyczne kierunki działań mogą mieć szczególne znaczenie w wymiarze gospodarczym, jak i społecznym, wspierając kształtowanie polityki sektorowej, decyzje inwestycyjne oraz organizację systemów transportowych w warunkach aktualnych i przyszłych zagrożeń. Wobec stale zmieniających się uwarunkowań oraz ryzyka wystąpienia kolejnych kryzysów podjęcie badań w zakresie tej tematyki staje się niezbędne dla zapewnienia bardziej stabilnego i bezpiecznego przepływu osób oraz towarów, a tym samym zaspokojenia generowanych potrzeb i dalszego rozwoju gospodarczego.

Strukturę rozprawy doktorskiej podporządkowano spójnemu i syntetycznemu przedstawieniu wyników oraz wniosków z przeprowadzonych badań.

Rozdział pierwszy stanowi kontekst dla całości analiz oraz uzasadnia podjęcie tematu rozprawy w oparciu o przegląd aktualnego stanu wiedzy w zakresie poruszonej problematyki.

W drugim rozdziale zaprezentowano przyjętą metodykę badań oraz charakterystykę cyklu publikacji stanowiących podstawę niniejszego opracowania.

Trzeci rozdział rozprawy przedstawia wyniki badań uzyskane w artykułach składających się na cykl. W pierwszej kolejności opracowano typologię współczesnych kryzysów powiązanych z transportem i rozpatrzono kwestię czynników środowiskowo-gospodarczych kształtujących jego funkcjonowanie. Dalej skoncentrowano się na kryzysie zdrowotnym oraz badaniu jego wpływu na kondycję pasażerskiego transportu. Następnie przeanalizowano wybrane systemy transportowe w Polsce w świetle kryzysów militarnych i społecznych. Usystematyzowano także modele matematyczne rozpatrywane w toku całych badań wraz z syntetycznym zestawieniem ich zastosowań.

Na zakończenie, w rozdziale czwartym, podsumowano przeprowadzone badania, sformułowano wnioski końcowe, a także określono kierunki dalszych prac badawczych.

2. ZAŁOŻENIA I OBSZAR BADAWCZY ROZPRAWY

Rozprawę doktorską stanowi cykl pięciu powiązanych tematycznie artykułów naukowych (**P1–P5**). Publikacje te zostały zamieszczone w polskich **(P4)** oraz zagranicznych czasopismach **(P1–P3, P5)**. Wszystkie te wydawnictwa znajdują się na wykazie czasopism punktowanych, określonym komunikatem Ministra Nauki z dnia 5 stycznia 2024 r. [65]. Łączna liczba punktów MEiN za publikacje uwzględnione w cyklu wynosi **510**, a sumaryczny Impact Factor (IF) czasopism to **9,3**. Wykaz artykułów składających się na cykl publikacji przedstawiono w tabeli 2.1.

Tabela 2.1. Wykaz artykułów stanowiących cykl publikacji

Ozn.	Dane bibliograficzne publikacji	Punkty wg MEiN, IF
P1	**Sobczuk, S.**; Borucka, A. Recent Advances for the Development of Sustainable Transport and Their Importance in Case of Global Crises: A Literature Review, *Applied Sciences* 2024, *14* (22), 10653, DOI: https://doi.org/10.3390/app142210653.	100 pkt, IF = 2,5
P2	Borucka, A.; **Sobczuk, S.** Analysis of the Relationship Between Energy Consumption in Transport, Carbon Dioxide Emissions and State Revenues: The Case of Poland, *Energies* 2025, *18* (9), 2291, DOI: https://doi.org/10.3390/en18092291.	140 pkt, IF = 3,2
P3	**Sobczuk, S.**; Borucka, A. Passenger air transport in Poland and selected European countries in the face of COVID-19: a post-pandemic comparative analysis, *Sustainability* 2025, *17* (24), 11026, DOI: https://doi.org/10.3390/su172411026.	100 pkt, IF = 3,3
P4	**Sobczuk, S.**; Borucka, A. Passenger traffic in Polish seaports in the face of the COVID-19 pandemic, *Zeszyty Naukowe Politechniki Morskiej w Szczecinie – Scientific Journals of the Maritime University of Szczecin* 2025, *81* (153), 57-66, DOI: https://doi.org/10.17402/631.	70 pkt, IF = 0,3
P5	**Sobczuk, S.**; Borucka, A.; Kler, P. Application of selected mathematical models for analysis and evaluation of the functioning of transport processes in crisis situations, *European Research Studies Journal* 2025, *28* (4), 1175-1193, DOI: https://doi.org/10.35808/ersj/4166.	100 pkt

Publikacje **P1-P5** obejmują autorskie podejście do badania odporności procesów transportowych w warunkach współczesnych wyzwań oraz zagrożeń o podłożu środowiskowym, gospodarczym, zdrowotnym, społecznym i militarnym. W rozprawie zastosowano metody analizy i oceny funkcjonowania procesów transportowych oparte na modelach matematycznych i danych statystycznych. Skupiono się w szczególności na funkcjonowaniu polskiego systemu transportowego i odniesiono do konkretnych zakłóceń.

Wykorzystano przede wszystkim modele szeregów czasowych, modele ekonometryczne oraz algorytmy uczenia maszynowego, których zastosowanie umożliwiło analizę zmian i zależności w procesach transportowych oraz ocenę skutków kryzysów. Na podstawie uzyskanych wyników opracowano rekomendacje i propozycje rozwiązań, które mogą znaleźć praktyczne zastosowanie w sferze gospodarczej i społecznej, w szczególności jako wsparcie dla instytucji publicznych, organizatorów transportu, przewoźników – zarówno w odniesieniu do obecnych uwarunkowań, jak i przyszłych kryzysów o podobnej genezie. Wkład przeprowadzonych badań jest zatem istotny z uwagi na fundamentalną rolę transportu jako sektora, którego prawidłowe funkcjonowanie warunkuje mobilność społeczeństwa i ciągłość powiązań gospodarczych, a tym samym zaspokajanie potrzeb przewozowych ludności, stabilność gospodarki oraz jej trwały rozwój.

Poza publikacjami stanowiącymi cykl powiązanych tematycznie artykułów autor rozprawy prowadził dodatkowe badania. Ich wynikiem są nieuwzględnione w cyklu publikacje uzupełniające. Prace te poszerzają kontekst prowadzonych badań oraz stanowią spójne dopełnienie zasadniczych wyników rozprawy. Łączna liczba punktów MEiN za te opracowania wynosi **460**, a sumaryczny Impact Factor czasopism to **6,4**. Wykaz publikacji uzupełniających przedstawiono w tabeli 2.2.

Tabela 2.2. Wykaz publikacji uzupełniających cykl

Ozn.	Dane bibliograficzne publikacji	Punkty wg MEiN, IF
U1	Borucka, A.; **Sobczuk, S.** Electromobility in the world: comparison of electric vehicle sales dynamics in selected regions, *Interdisciplinary Management Research XXI* 2025, *21*, 13-28.	-
U2[a]	**Sobczuk, S.**; Borucka, A.; Kurzyk, E. Development trends in the field of electromobility in Poland. w: Rudawska, A. (red.), *Innovative Technologies in Production Engineering*, Wydawnictwo Politechniki Lubelskiej, 2024.	20 pkt
U3	**Sobczuk, S.**; Jaroń, A.; Mazur, M.; Borucka, A. Renewable Energy and CO_2 Emissions: Analysis of the Life Cycle and Impact on the Ecosystem in the Context of Energy Mix Changes, *Energies* 2025, *18* (13), 3332, DOI: https://doi.org/10.3390/en18133332.	140 pkt, IF = 3,2
U4	**Sobczuk, S.**; Świderski, A. Assessment of the impact of the COVID-19 pandemic on selected areas of the transport sector in Poland. *Communications of International Proceedings* 2024, *2024* (11), 4439824, DOI: https://doi.org/10.5171/2024.4439824.	20 pkt
U5	**Sobczuk, S.** Transport in the tourist services sector in Poland during the crisis caused by the COVID-19 pandemic. *WUT Journal of Transportation Engineering* 2024, 138, 5–18, DOI: https://www.doi.org/10.5604/01.3001.0054.5151.	20 pkt
U6	**Sobczuk, S.**; Borucka A. Rail passenger transport in Poland in the face of an epidemic threat: effects from the COVID-19 pandemic, *Advances in Transdisciplinary Engineering* 2025, *83*, 340-349, DOI: https://doi.org/10.3233/ATDE251453.	20 pkt
U7	Świderski, A.; **Sobczuk, S.**; Borucka, A. Analysis of changes in transport processes in Warsaw public transport in the face of disruptions in 2019-2022. *Scientific Journal of Silesian University of Technology. Series Transport* 2024, *124*, 229–241, DOI: https://www.doi.org/10.20858/sjsutst.2024.124.16.	100 pkt, IF = 0,7
U8	**Sobczuk, S.** Selection of means of transport in epidemic threat conditions using the multi-criteria comparative analysis method (MCA), w: Burduk, A. (red.), *Intelligent Systems in Production Engineering and Maintenance IV. ISPEM 2025. Lecture Notes in Mechanical Engineering*, Springer, 2025, ss. 56-73. DOI: https://doi.org/10.1007/978-3-032-01517-4 5.	20 pkt
U9	Borucka, A.; **Sobczuk, S.**, The Use of Machine Learning Methods in Road Safety Research in Poland, *Applied Sciences* 2025, *15* (2), 861, DOI: https://doi.org/10.3390/app15020861.	100 pkt, IF = 2,5
U10	Borucka, A.; **Sobczuk, S.**; Sobecki, G. Road accidents in Poland in the context of selected factors and dynamic development of motorization, *Advances in Transdisciplinary Engineering* 2024, *63*, 54-63, DOI: https://doi.org/10.3233/ATDE241180.	20 pkt

[a] Status pracy to przyjęta do publikacji – potwierdzone zaświadczeniem o akceptacji.

Na podstawie przeprowadzonej kwerendy literatury sformułowano następujący główny problem badawczy:

Jak współczesne kryzysy wpływają na procesy transportowe oraz w jakim zakresie metody matematyczne mogą być wykorzystane do modelowania tych oddziaływań i wspierania funkcjonowania sektora transportu w obliczu zakłóceń o zróżnicowanym charakterze?

W celu znalezienia odpowiedzi na tak postawione pytanie, zdefiniowano następujące problemy szczegółowe:

PS1. W jaki sposób współczesne wyzwania środowiskowe i gospodarcze determinują funkcjonowanie oraz rozwój sektora transportu w Polsce?

PS2. W jaki sposób kryzysy zdrowotne wpływają na funkcjonowanie pasażerskiego transportu oraz jaki jest poziom zakłóceń i dynamika zmian w popycie na przewozy w wyniku takich zjawisk?

PS3. W jaki sposób kryzysy militarne wpływają na realizację przewozów pasażerskich w publicznym transporcie zbiorowym oraz jakie wzorce i czynniki kształtują bezpieczeństwo ruchu drogowego w Polsce w kontekście kryzysów społecznych?

Sformułowany problem główny oraz problemy szczegółowe stanowiły podstawę do określenia celu rozprawy, którym jest:

Przeprowadzenie analizy i oceny oddziaływania zróżnicowanych kryzysów na funkcjonowanie procesów transportowych, identyfikacja zakłóceń i wzorców ryzyka z wykorzystaniem metod matematycznych oraz opracowanie rekomendacji wspierających sektor transportu w warunkach niepewności.

Uwzględniając sformułowane problemy i cel badawczy postawiono następującą hipotezę główną:

Oddziaływanie współczesnych kryzysów na procesy transportowe ma charakter zróżnicowany i zależy zarówno od rodzaju zakłócenia, jak i od cech organizacyjnych oraz strukturalnych danego procesu transportowego, przy czym zastosowanie metod matematycznych umożliwia identyfikację prawidłowości tych oddziaływań oraz ocenę odporności sektora transportu.

Do tak przyjętej hipotezy głównej postawiono hipotezy szczegółowe:

HS1. Wzrost zużycia energii końcowej w transporcie prowadzi do zwiększenia emisji dwutlenku węgla z transportu oraz współkształtuje poziom dochodów budżetu państwa, a stabilne długookresowe zależności pomiędzy tymi zmiennymi wskazują na wpływ współczesnych wyzwań środowiskowych i gospodarczych na transport w Polsce.

HS2. Kryzysy zdrowotne o podłożu epidemicznym prowadzą do spadku liczby przewożonych pasażerów oraz zaburzeń dynamiki popytu na przewozy w Polsce, a skala załamania i przebieg zmian są zróżnicowane pomiędzy gałęziami transportu.

HS3. Kryzysy militarne prowadzą do zmiany kierunku trendu i wzrostu tempa zmian liczby pasażerów oraz wykonanej pracy przewozowej w publicznym transporcie zbiorowym w aglomeracji warszawskiej, a kryzysy społeczne związane z wypadkami drogowymi w Polsce wykazują zróżnicowanie ciężkości ich skutków oraz powtarzalne wzorce ryzyka determinowane czynnikami występowania zdarzeń.

Określony obszar badań oraz przyjęte założenia implikują ograniczenia badawcze:

- Przeprowadzone badania odnoszą się w szczególności do polskiego systemu transportowego, co wynika z przyjętego zakresu przestrzennego i dostępności danych statystycznych, w związku z czym ewentualne uogólnienie wyników badań i odniesienie uzyskanych wniosków do innych państw lub regionów powinno uwzględniać specyfikę ich uwarunkowań albo odpowiedni kontekst badawczy.
- Wykorzystano dane wtórne pochodzące z oficjalnych źródeł statystycznych, których zakres oraz ciągłość były zależne od instytucji udostępniających, a sposób raportowania mógł zmieniać się w czasie, co było konieczne do uwzględnienia przy interpretacji wyników oraz prowadzeniu analiz porównawczych.
- Zastosowane modele matematyczne opierają się na określonych założeniach formalnych, spełnionych w analizowanych przypadkach, jednak przy dalszym wykorzystaniu, zwłaszcza w odniesieniu do nowych zjawisk kryzysowych, mogą wymagać powtórnej weryfikacji.
- Współczesne kryzysy mają złożony i wielowymiarowy charakter, co ogranicza możliwość całkowitej separacji oddziaływania poszczególnych czynników na funkcjonowanie procesów transportowych.
- Wskazane kierunki działań i sformułowane rekomendacje mają charakter postulatywny, a ich praktyczna implementacja wymaga każdorazowo pogłębionej analizy oraz rozpoznania lokalnych, specyficznych uwarunkowań.

Metodykę badań oparto na założeniach prezentowanych w literaturze [66–68], które stanowiły podstawę doboru narzędzi i procedur badawczych szczegółowo opisanych w pozycjach [69–72], zaimplementowanych i zastosowanych na potrzeby badań własnych w publikacjach **P1–P5**.

Prace badawcze prowadzono etapami, poprzez rozwiązywanie zdefiniowanych problemów badawczych (**PS1–PS3**). Ich zestawienie wraz z metodami badawczymi, a także odniesieniem do publikacji stanowiących cykl pokazano w tabeli 2.3.

Tabela 2.3. Zestawienie publikacji stanowiących cykl oraz metod badawczych w ramach rozwiązania problemów badawczych

<table>
<tr><th>Problem badawczy</th><th>Publikacja stanowiąca cykl</th><th>Metody badawcze</th></tr>
<tr><td rowspan="2">PS1</td><td>P1</td><td>• metoda analizy i krytyki piśmiennictwa (źródeł)
• metoda analizy i konstrukcji logicznej</td></tr>
<tr><td>P2</td><td rowspan="3">• metoda analizy i krytyki piśmiennictwa (źródeł)
• metoda analizy i konstrukcji logicznej
• metoda statystyczna
• metoda symulacji komputerowej (modelowania)</td></tr>
<tr><td rowspan="2">PS2</td><td>P3</td></tr>
<tr><td>P4</td></tr>
<tr><td>PS3</td><td>P5</td><td>• metoda analizy i krytyki piśmiennictwa (źródeł)
• metoda analizy i konstrukcji logicznej</td></tr>
</table>

W celu rozwiązania problemu badawczego podjętego w niniejszej rozprawie zaproponowano autorskie podejście w zakresie badania procesów transportowych w warunkach zakłóceń o zróżnicowanym charakterze. Postępowanie to obejmuje:

- opracowanie typologii kryzysów istotnych dla funkcjonowania procesów transportowych,
- identyfikację i charakterystykę wzajemnych uwarunkowań pomiędzy funkcjonowaniem transportu a współczesnymi kryzysami,
- modelowanie matematyczne zależności oraz zmian zachodzących w funkcjonowaniu procesów transportowych w warunkach kryzysów na wybranych przykładach,
- opracowanie rekomendacji oraz wskazanie propozycji rozwiązań zorientowanych na zwiększenie odporności sektora transportu w obliczu istniejących wyzwań i przyszłych kryzysów.

W kolejnym rozdziale przedstawiono badania składające się na cykl tematycznie powiązanych artykułów naukowych, wraz ze szczegółowym opisem zastosowanych metod i narzędzi badawczych oraz prezentacją uzyskanych wyników.

3. CYKL POWIĄZANYCH TEMATYCZNIE ARTYKUŁÓW NAUKOWYCH

3.1. Transport wobec wyzwań środowiskowych i gospodarczych [publikacje P1–P2]

W publikacji **P1** w pierwszej kolejności dokonano usystematyzowania i doprecyzowania pojęcia kryzysu, aby zapewnić spójną definicję na potrzeby prowadzonych rozważań naukowych, a następnie przeanalizowano współczesne zdarzenia kryzysowe pod kątem ich oddziaływania na transport. Przeprowadzony w artykule przegląd literatury pozwolił na zidentyfikowanie kluczowych zdarzeń w perspektywie od początku XXI wieku do 2025 r., które zestawiono w tabeli 3.1.1.

Tabela 3.1.1. Zbiorcze zestawienie kryzysów obserwowanych od początku XXI wieku

Kryzys	Okres/charakter występowania
Globalny kryzys finansowy	2008–2009
Pandemia grypy A/H1N1v	2009–2010
Kryzys zadłużenia w strefie euro	2010–2018
Epidemia wirusa Ebola	2014–2016
Kryzys migracyjny w Europie	od 2015
Pandemia COVID-19	2020–2023
Wojna rosyjsko-ukraińska	od 2022
Wojna w Strefie Gazy	od 2023
Pożary lasów w Europie Południowej	2024
Zakłócenia w systemach energetycznych w Europie	2025
Utrzymująca się skala i ciężkość wypadków drogowych	Charakter długookresowy
Postępująca degradacja środowiska naturalnego	
Wzrost globalnych temperatur	
Intensyfikacja ekstremalnych zjawisk pogodowych	

Kryzysy mogą być klasyfikowane na różne sposoby – najczęściej w zależności od ich genezy oraz obszarów, których dotyczą. Jednoznaczna i w pełni obiektywna klasyfikacja nie jest jednak możliwa. Przede wszystkim każde ze zdarzeń ma unikalne cechy oraz wiąże się z konsekwencjami odmiennymi pod względem skali i zasięgu. Poza tym kryzysy często mają wiele przyczyn i skutków, które wzajemnie się przenikają. Na przykład wybuch pandemii COVID-19 w 2020 r., poza wpływem na zdrowie i życie ludności, okazał się poważny w skutkach dla globalnej gospodarki. Z kolei kryzys finansowy w 2008 r., oprócz załamania na światowych rynkach, doprowadził również do poważnych problemów społecznych. Zjawiska związane ze zmianami klimatu oraz narastającą presją klimatyczną, poza skutkami środowiskowymi, mają również istotny wpływ na gospodarkę, m.in. poprzez konieczność ograniczania emisji, dostosowanie do wymagań transformacji energetycznej oraz wzrost kosztów energii i transportu. W oparciu o przegląd literatury dotyczącej oddziaływania współczesnych kryzysów na transport dokonano identyfikacji i usystematyzowania ich głównych typów [73]. W procesie tym – jako punkt odniesienia – wykorzystano dotychczasowe ustalenia dotyczące rozróżniania kryzysów [46–48], uzupełniając je o zagrożenia militarne, co jest uzasadnione ze względu na nasilające się w ostatnich latach napięcia geopolityczne w wielu regionach świata. Opracowaną w **P1** typologię, wraz z charakterystyką oddziaływania poszczególnych typów kryzysów na funkcjonowanie transportu przedstawiono w tabeli 3.1.2

Tabela 3.1.2. Typologia współczesnych kryzysów oddziałujących na funkcjonowanie transportu

Typ kryzysu	Oddziaływanie na funkcjonowanie transportu
Środowiskowy	• konieczność ograniczania emisji gazów cieplarnianych • ograniczenia dostępności surowców do produkcji pojazdów • rosnące zapotrzebowanie na bardziej ekologiczne formy transportu • rosnące ceny paliw konwencjonalnych • presja kosztowa związana z transformacją energetyczną transportu
Gospodarczy	• mniejszy popyt na podróże ze względu na koszty • spadek wolumenu przewozów towarowych • zwrot społeczeństwa w kierunku transportu publicznego • ograniczenie wydatków gospodarstw domowych na transport
Zdrowotny	• spadek popytu na przewozy pasażerskie w transporcie publicznym • spadek zainteresowania podróżami turystycznymi • zmiana preferencji dotyczących wyboru środków transportu • restrykcje w ruchu międzynarodowym i zmiany organizacji przewozów • zakłócenia w łańcuchach dostaw i zmiany w strukturach przewożonych towarów
Społeczny	• spadek popytu na podróże z obawy o bezpieczeństwo • problemy z zapewnieniem bezpieczeństwa infrastruktury transportowej • sceptyczne nastawienie do obowiązujących przepisów ruchu drogowego • wysokie koszty społeczno-ekonomiczne zdarzeń drogowych • rosnąca presja na zmiany w infrastrukturze i regulacjach prawnych • nierówność w dostępie do transportu
Militarny	• zniszczenia infrastruktury transportowej • ograniczenia przestrzeni powietrznej i morskiej • zawieszenie połączeń międzynarodowych • wymuszone migracje ludności i zmiany w mobilności w regionach przyjmujących • zagrożenie atakiem dla realizowanych przewozów

Powyższa typologia współczesnych kryzysów powiązanych z transportem ukierunkowała realizację dalszych badań obejmujących modelowanie matematyczne oddziaływania tych zjawisk na procesy transportowe.

Rozpoczęto od analizy relacji zachodzących pomiędzy czynnikami środowiskowo-gospodarczymi wpływającymi na funkcjonowanie i zrównoważony rozwój transportu. W publikacji **P2** wykorzystano w tym celu podejście oparte na metodzie kointegracji Johansena, która pozwoliła na analizę długookresowych zależności między wieloma szeregami czasowymi. W badaniu uwzględnione zostały trzy zmienne: całkowite wykorzystanie energii końcowej w transporcie (TFECT), emisje dwutlenku węgla pochodzące z działalności transportowej (CO_2T), a także dochody budżetu państwa (GREV). W ten sposób możliwe było jednoczesne powiązanie środowiskowego i gospodarczego wymiaru funkcjonowania transportu. Utworzone szeregi czasowe zmiennych TFECT i CO_2T odnosiły się bezpośrednio do presji środowiskowej generowanej przez popyt na przewozy, natomiast GREV stanowił odniesienie do kondycji fiskalnej państwa w stosunku do wielkości gospodarki oraz związanych z tym możliwości finansowania działań publicznych. Analizy przeprowadzono dla Polski w okresie 1990–2022, co zapewniło wystarczającą liczbę obserwacji do zastosowania metody kointegracji Johansena oraz identyfikacji stabilnych, długookresowych zależności.

Na wstępie tego badania zweryfikowano własności stochastyczne szeregów czasowych wykorzystując trzy różne testy stacjonarności, tj. ADF, PP i KPSS. Wyniki każdego z przeprowadzonych testów wskazywały, że wszystkie szeregi czasowe reprezentowane przez dane surowe są niestacjonarne, natomiast wykazują stacjonarność po pierwszym różnicowaniu. Potwierdziło to spełnienie warunków do przeprowadzenia testu kointegracji Johansena.

Zasadniczą część modelowania matematycznego zrealizowano według procedury Johansena, która opiera się na wektorowym modelu korekcji błędów. Przed przeprowadzeniem testów kointegracji dokonano wyboru optymalnego rzędu opóźnień biorąc pod uwagę wartości kryteriów informacyjnych (AIC, HQC, SC, FPE). Następnie dokonano sprawdzenia liczby relacji kointegracyjnych wykorzystując statystyki testowe Trace oraz Max-Eigenvalue, których wyniki pozwoliły zakładać istnienie dwóch wektorów kointegracyjnych. Skonstruowano również macierz obciążeń (*ang. loading matrix*), której analiza pokazała, jak każdy z szeregów reaguje na odchylenia od długookresowej równowagi. W rezultacie procedura potwierdziła, że szeregi czasowe zmiennych TFECT, CO_2T i GREV tworzą kombinacje liniowe, które pozostają w równowadze w długim okresie. W związku z tym możliwe było estymowanie modelu VECM. Wyznaczona została macierz wektorów kointegrujących β wraz ze składnikami trendu, którą przedstawiono w tabeli 3.1.3.

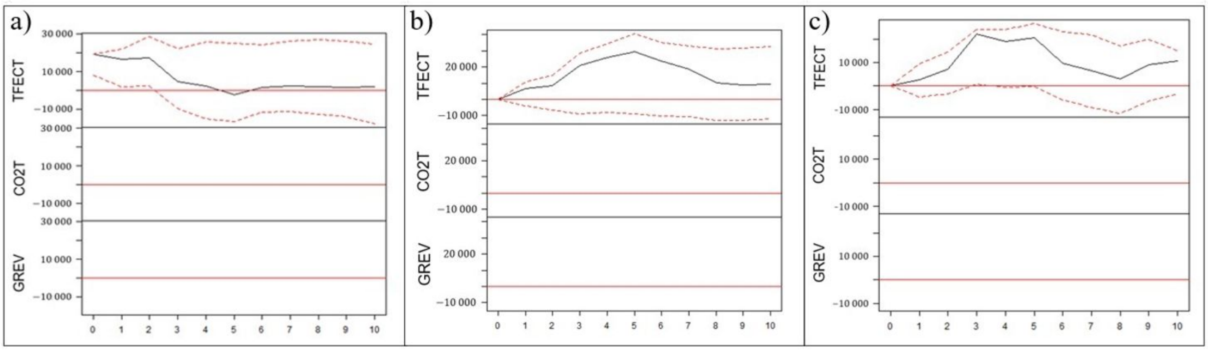
Tabela 3.1.3. Macierz wektorów kointegrujących β z dołączonymi współczynnikami trendu

	ect1	ect2
TFECT.L5	1	$6{,}776 \times 10^{-21}$
CO_2T.L5	0	1
GREV.L5	−34483,64	−2,467
TREND.L5	−26828,31	−1,807

Jak pokazano w tabeli 3.1.3, zidentyfikowano dwie relacje kointegracyjne – ect1 i ect2. W pierwszej relacji szeregiem referencyjnym był TFECT, przy czym CO_2T nie wchodził do tej relacji, natomiast GREV oraz trend miały istotne, ujemne współczynniki. Druga relacja kointegracyjna została znormalizowana względem CO_2T, a współczynniki dla GREV i trendu uzyskały ujemne wartości. Opierając się na określonych współczynnikach relacje ect1 oraz ect2 wyrażono w postaci równań – odpowiednio (1) i (2):

$$TFECT.L5 - 34{,}483.64 \times GREV.L5 - 26{,}828.31 \times TREND.L5 = 0 \quad (1)$$
$$CO_2T.L5 - 2.467 \times GREV.L5 - 1.807 \times TREND.L5 = 0 \quad (2)$$

Po ustaleniu relacji długookresowej równowagi dokonano jeszcze estymacji funkcji odpowiedzi impulsowej. Analiza IRF pozwoliła dokładniej zrozumieć zarówno krótko-, i długookresową dynamikę pomiędzy szeregami czasowymi, a także zidentyfikować główne kanały transmisji (tzw. szoki w systemie). Funkcje odpowiedzi na impuls dla rozpatrywanych szeregów czasowych wraz z 95% przedziałami ufności przedstawiono na rysunku 3.1.1.



Rys. 3.1.1. Funkcje odpowiedzi na impuls dla szeregów: a) TFECT, b) CO_2T, c) GREV

Uzyskane w toku modelowania matematycznego wyniki potwierdziły, że wszystkie analizowane szeregi czasowe są ze sobą powiązane w długim okresie, przy czym zidentyfikowane zależności charakteryzują się zróżnicowaną intensywnością oraz dynamiką czasową. Całkowite zużycie energii końcowej w transporcie jest głównym czynnikiem kształtującym zarówno poziom emisji CO_2 z transportu, jak i wielkość dochodów budżetu państwa. Wzrost TFECT prowadzi do istotnego, choć rozłożonego w czasie wzrostu emisji oraz przekłada się na poziom wpływów budżetowych. Jednocześnie wykazano, że szereg czasowy

CO_2T reaguje na TFECT, ale także na własne szoki co sugeruje, że emisje CO_2 z transportu mają charakter samowzmacniający. Dochody publiczne, pomimo istotnego powiązania ze zużyciem energii w sektorze transportu, wykazują mniej jednoznaczne reakcje, wskazując na pośredni przebieg tej zależności [74]. Tak zidentyfikowane relacje pozwoliły na sformułowanie implikacji oraz możliwych kierunków działań w zakresie funkcjonowania i rozwoju sektora transportu:

- Wprowadzenie akcyzy paliwowej zależnej jednocześnie od emisyjności paliwa i poziomu zużycia energii w transporcie. Mechanizm ten powinien działać progowo, aby po przekroczeniu określonego poziomu zużycia energii w sektorze automatycznie wzrastała stawka dla paliw o najwyższej emisyjności. Taki instrument pozwoliłby ograniczać wzrost emisji w okresach największej intensyfikacji zużycia paliw w transporcie, a przy tym sprzyjałby utrzymaniu stabilnych wpływów budżetowych.
- Okresowy wzrost dochodów publicznych po wzroście zużycia energii w transporcie powinien być wykorzystywany do tworzenia rezerw finansowych na potrzeby przyszłych zakłóceń w sektorze transportu, w szczególności związanych ze wzrostem cen paliw, kryzysami energetycznymi lub zaostrzeniem regulacji klimatycznych. Ograniczyłoby to konieczność nagłego zwiększania wydatków na transport w sytuacji wystąpienia kryzysu.
- Częściowe przekazywanie wpływów z podatków paliwowych samorządom odpowiedzialnym za transport lokalny, z przeznaczeniem tych środków na działania zwiększające odporność systemu transportowego. Część wpływów z akcyzy powinna być kierowana do jednostek samorządu terytorialnego na utrzymanie rezerw taborowych, modernizację transportu publicznego oraz tworzenie lokalnych funduszy kryzysowych (m.in. na okres nagłych wzrostów cen paliw lub czasowego spadku dochodów publicznych). Pozwoliłoby to skrócić czas reakcji na zakłócenia i ograniczyć ryzyko destabilizacji transportu lokalnego w sytuacjach kryzysowych.
- Przeznaczenie większej części środków z EU ETS na modernizację obszarów transportu najbardziej zależnych od paliw ropopochodnych, przede wszystkim transportu publicznego i drogowego transportu towarowego. Środki te powinny być kierowane na elektryfikację autobusów, pojazdów ciężarowych oraz rozwój infrastruktury ładowania. Ograniczyłoby to ryzyko zakłóceń procesów transportowych w sytuacji wzrostu cen ropy lub ograniczenia jej podaży.

Przeprowadzone w badaniu modelowanie matematyczne, obejmujące metodę kointegracji Johansena, model VECM oraz analizę funkcji odpowiedzi impulsowej uwydatnia rolę tego typu podejść w analizach dotyczących funkcjonowania transportu w warunkach współczesnych kryzysów o podłożu gospodarczym i środowiskowym. Przyjęta procedura pozwoliła nie tylko na identyfikację stabilnych relacji długookresowych pomiędzy zużyciem energii końcowej w transporcie, emisjami dwutlenku węgla z transportu oraz dochodami budżetu państwa, lecz także na ocenę zróżnicowanych mechanizmów dostosowawczych, zachodzących po odchyleniach od równowagi. Istotnym elementem przeprowadzonej analizy było określenie znaczenia poszczególnych szeregów czasowych w całym układzie, w szczególności dominującej roli TFECT jako czynnika silnie inicjującego zmiany o charakterze środowiskowym i fiskalnym, choć z rozkładającym się w czasie efektem. Zidentyfikowane relacje długookresowej równowagi mogą stanowić wsparcie w kontekście kształtowania przyszłej polityki krajowej, aby z jednej strony dążyć do rozwoju gospodarczego, a tym samym również zwiększać dochody budżetowe, ale jednocześnie optymalizować zużycie energii i ograniczać emisje CO_2 wynikające z rosnącego zapotrzebowania na transport. Z kolei analiza IRF pozwoliła na dostarczenie dodatkowych informacji na temat rozkładu efektów w czasie wskazując, że skutki zaburzeń energetycznych oraz emisyjnych ujawniają się w sferze fiskalnej w sposób pośredni i rozłożony w czasie, co może wspierać planowanie stopniowych działań korygujących. Modelowanie matematyczne zastosowane w badaniu umożliwiło zatem pogłębioną analizę zależności zmiennych środowiskowych i ekonomicznych mających przełożenie na warunki otoczenia dla funkcjonowania procesów transportowych, dostarczając podstaw do bardziej świadomego kształtowania długookresowych kierunków polityki wobec transportu, sprzyjających zrównoważonemu rozwojowi oraz wzmacnianiu odporności sektora na kryzysy.

Zidentyfikowane długookresowe relacje wskazują, że ograniczanie presji środowiskowej sektora transportu nie może odbywać się bez ingerencji w strukturę zużycia energii. Dlatego wobec narastających wyzwań środowiskowych i energetycznych oraz ich konsekwencji gospodarczych coraz większego znaczenia nabierają rozwiązania technologiczne, zorientowane na ograniczanie emisyjności transportu i zmniejszanie jego zależności od paliw konwencjonalnych. W tym kontekście w publikacji **P1**, w wyniku przeglądu najnowszych postępów i innowacji w transporcie, jako jedną z kluczowych kategorii rozwiązań wskazano technologie napędów w pojazdach. Znaczenie tego obszaru stało się podstawą do dalszych badań ukierunkowanych na analizę rozwoju elektromobilności i związanych z tym uwarunkowań rynkowych.

W publikacji **U1** skoncentrowano się na porównawczej analizie dynamiki rozwoju elektromobilności w Chinach, Unii Europejskiej oraz Stanach Zjednoczonych, biorąc pod uwagę dwa segmenty rynku: pojazdy w pełni elektryczne i hybrydowe typu plug-in. W badaniu zastosowano skumulowany roczny wskaźnik wzrostu, który pozwolił na porównanie dynamiki sprzedaży pojazdów BEV oraz PHEV pomiędzy regionami o zróżnicowanej skali i strukturze rynków. Wskaźnik GREV stanowił stabilną miarę porównawczą ogólnych trendów rynkowych, minimalizującą wpływ wahań lub przejściowych szoków, takich jak wybuch pandemii 2020 r. czy zaburzenia w globalnych łańcuchach dostaw. Uzupełniająco dokonano zestawienia liczby pojazdów sprzedanych z liczbą pojazdów pozostających w użytkowaniu (stock), aby ocenić wzorce utrwalania się elektromobilności w strukturach systemów transportowych poszczególnych regionów. Wyniki wskazały na silne zróżnicowanie pomiędzy częściami świata. Najwyższe wartości wskaźnika CAGR odnotowano w Chinach, gdzie tempo wzrostu sprzedaży zarówno pojazdów BEV (*CAGR = 0,92*), jak i PHEV (*CAGR = 1,00*) było najwyższe spośród analizowanych regionów, czemu towarzyszył również największy poziom nasycenia rynku pojazdami o takich napędach. W UE zaobserwowano szczególnie wysoką dynamikę rozwoju segmentu PHEV (*CAGR = 1,02*), co podkreśla kluczową rolę technologii przejściowych w procesie elektryfikacji sektora transportu. Rynek USA charakteryzował się dominacją BEV (*CAGR = 0,69*) przy niskiej dynamice rozwoju PHEV (*CAGR = 0,35*), odzwierciedlając odmienny model adaptacji technologicznej i strukturę popytu na pojazdy elektryczne [75].

Wyniki publikacji **U1** pokazują, że zdolność transportu do stabilnego przechodzenia na elektromobilność w dużej mierze zależy od działań rządów, w tym od kształtowania polityki sprzyjającej posiadaniu pojazdów elektrycznych, a także od kwestii takich jak dostęp do infrastruktury i preferencji konsumenckich podczas zakupu. Rozwiązania niskoemisyjne w pojazdach stanowią istotny element odpowiedzi na współczesne wyzwania środowiskowe i gospodarcze, wynikające z konieczności realizacji długookresowych celów polityki klimatycznej, przy równoczesnym wzroście mobilności i intensyfikacji pracy przewozowej. Na tym tle badanie potwierdza, że elektromobilność, zwłaszcza w segmencie BEV, sprzyja trwałej redukcji presji emisyjnej w transporcie, natomiast technologie hybrydowe pełnią funkcję stabilizującą w okresie przejściowym, umożliwiając stopniowe dostosowanie systemów transportowych do celów zrównoważonego rozwoju.

Poza przeprowadzeniem analiz dla wybranych regionów świata podjęto także badania ograniczone wyłącznie do rynku polskiego. W publikacji **U2** rozważania dotyczące rozwoju elektromobilności w Polsce osadzono w kontekście celów klimatycznych i regulacji UE zakładających redukcję emisji gazów cieplarnianych w transporcie o 90% do 2040 r. względem poziomu z 1990 r., przy jednoczesnym wskazaniu transportu drogowego jako gałęzi o najwyższym poziomie emisyjności. Badanie rozpoczęto od analizy zmian w strukturze krajowego parku pojazdów mechanicznych oraz rejestracji samochodów osobowych według rodzaju stosowanego paliwa w latach 2017–2022. Zwrócono uwagę na systematyczny wzrost liczby samochodów osobowych w Polsce (o 3,94 mln, tj. 17,42%), przy relatywnie stabilnym udziale tej kategorii w strukturze ogółu pojazdów (ok. 75,9%). Jednocześnie zauważono wyraźne załamanie liczby rejestracji w 2020 r., związane z pandemią i towarzyszącymi jej zakłóceniami gospodarczymi, co ujawniło podatność rynku motoryzacyjnego na tego typu zdarzenia. Następnie przeprowadzono analizę dynamiki rozwoju pojazdów w pełni elektrycznych oraz hybrydowych typu plug-in. Liczbę pojazdów BEV i PHEV w Polsce opisano za pomocą funkcji wykładniczych estymowanych metodą najmniejszych kwadratów. Wyznaczone parametry modeli oraz miary ich dopasowania do danych empirycznych zestawiono zbiorczo w tabeli 3.1.4.

Tabela 3.1.4. Parametry i miary dopasowania modeli funkcji wykładniczej dla BEV i PHEV

	Parametr modelu		**Współczynnik determinacji (R^2)**
	a	***b***	
BEV	3795	0,0450	0,99
PHEV	3890	0,0438	0,98

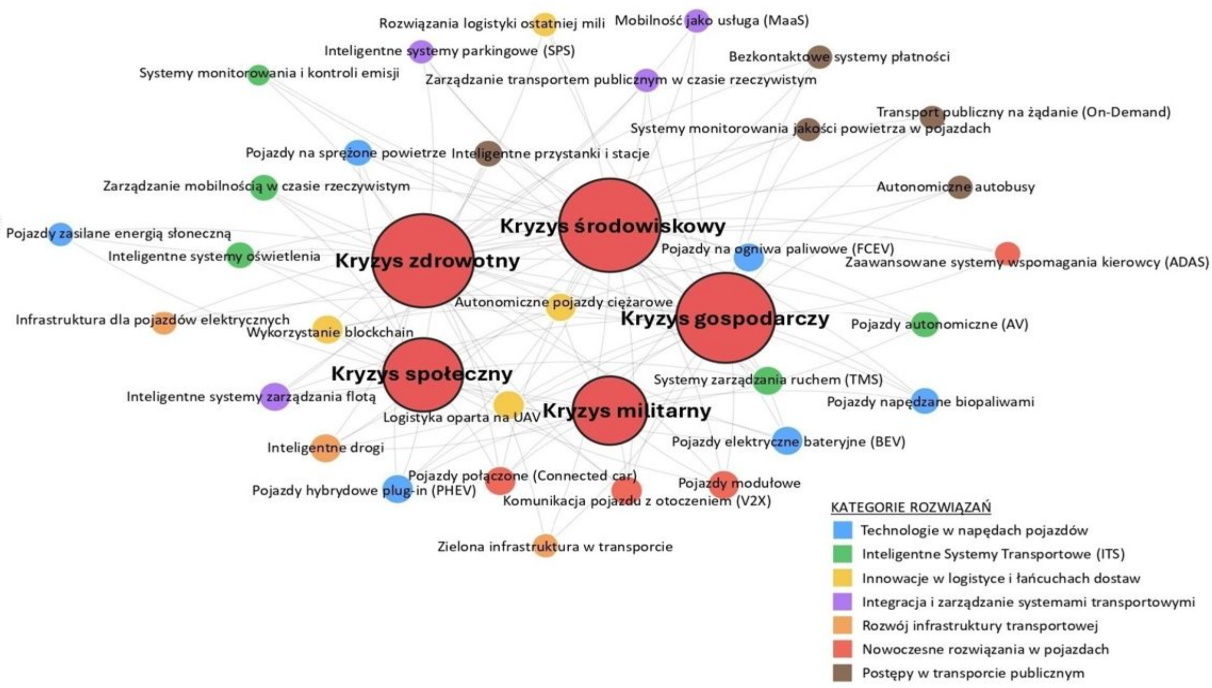
Wysokie wartości współczynnika R^2 potwierdzają bardzo dobre dopasowanie opracowanych modeli do danych empirycznych zarówno dla BEV, jak i PHEV. Porównanie wartości parametrów *b* wskazuje na nieco wyższą dynamikę przyrostu liczby pojazdów w pełni elektrycznych względem hybrydowych typu plug-in [76].

Uzyskane w **U2** wyniki potwierdzają wykładniczy charakter wzrostu liczby pojazdów elektrycznych oraz hybrydowych typu plug-in, co oznacza wyraźnie szybszą dynamikę zmian niż w przypadku modeli liniowych. Istotne jest przy tym, że nawet silne zakłócenia zewnętrzne o charakterze gospodarczym, w dużej mierze wynikające z pandemii COVID-19, a także towarzyszących jej zaburzeń w globalnych łańcuchach dostaw i procesach produkcyjnych, nie doprowadziły do wyhamowania tego procesu. Z jednej strony wskazuje to na relatywnie wysoką odporność obserwowanych tendencji rozwojowych elektromobilności na szoki oddziałujące na sektor transportu. Z drugiej natomiast akcentuje znaczenie instrumentów regulacyjnych, systemów wsparcia finansowego oraz postępu technologicznego dla dalszej, stabilnej elektryfikacji polskiego transportu.

Trzeba jednak nadmienić, że wzrost liczby pojazdów zasilanych energią elektryczną, których korzystny efekt środowiskowy ujawnia się głównie na etapie eksploatacji, wymaga także uwzględnienia emisyjności energii elektrycznej oraz uwarunkowań związanych z funkcjonowaniem sektora energetycznego, w tym jego odporności na potencjalne zakłócenia, zwłaszcza w warunkach rosnącego udziału odnawialnych źródeł energii. Wysoki udział niesterowalnych OZE, przy ograniczonej elastyczności sieci elektroenergetycznych oraz niewystarczających zdolnościach magazynowania, może prowadzić do poważnych zaburzeń w dostawach energii, czego przykładem był blackout w Hiszpanii i Portugalii w 2025 r., skutkujący paraliżem transportu i systemów łączności. W konsekwencji oznacza to, że rozwój elektromobilności należy rozpatrywać nie tylko przez pryzmat tempa elektryfikacji floty, lecz także emisyjności energii elektrycznej w całym cyklu jej życia oraz stabilności systemu elektroenergetycznego. Z tego względu w publikacji **U3** dokonano oceny cyklu życia energii elektrycznej wytwarzanej z fotowoltaiki oraz energetyki wiatrowej, z uwzględnieniem magazynów energii, jako elementu stabilizującego pracę systemu. Wykazano, że w polskich uwarunkowaniach technologiczno-eksploatacyjnych energia elektryczna z OZE nie jest zeroemisyjna w ujęciu całego cyklu życia. Jednostkowe emisje utrzymują się na poziomie odpowiednio ok. 55 g CO_2/kWh dla fotowoltaiki oraz 12 g CO_2/kWh dla energetyki wiatrowej. Ponadto zastosowano modele regresji liniowej, regresji wykładniczej oraz ARIMA w celu określenia horyzontu czasowego osiągnięcia zakładanego poziomu mocy zainstalowanej OZE w Polsce, warunkującego m.in. możliwość realizacji niskoemisyjnej elektromobilności w ujęciu systemowym. Otrzymane wyniki wskazały na istotne rozbieżności w momentach osiągnięcia 60 GW – odpowiednio 2066 r. w przypadku regresji liniowej, 2036 r. dla regresji wykładniczej i 2035 r. dla modelu ARIMA [77]. Badanie to dowodzi, że warunkiem racjonalnej, niskoemisyjnej elektromobilności jest nie tylko szybki wzrost liczby pojazdów zasilanych energią elektryczną, lecz przede wszystkim równoległa dekarbonizacja oraz uelastycznienie systemu energetycznego, zapewniające jego odporność na zakłócenia.

Należy zaznaczyć, że rozwiązania obejmujące alternatywne źródła zasilania pojazdów, wpisujące się w koncepcję rozwoju elektromobilności, stanowiły tylko jeden z aspektów szerszej analizy literatury przeprowadzonej w publikacji **P1**. Zgodnie z podejściem PRISMA w artykule dokonano systematycznego przeglądu aktualnego stanu badań dotyczących innowacji w zakresie rozwoju transportu zrównoważonego, w ramach którego zidentyfikowane rozwiązania zostały przyporządkowane do wyodrębnionych kategorii, a następnie przeanalizowane pod kątem ich znaczenia w kontekście wyzwań i potencjalnych zagrożeń.

Relacje pomiędzy przykładami rozwiązań w transporcie, a typami kryzysów, w obliczu których mogą one znaleźć zastosowanie, przedstawiono na rysunku 3.1.2.



Rys. 3.1.2. Mapa powiązań pomiędzy typami współczesnych kryzysów a rozwiązaniami w transporcie opisanymi w publikacji **P1**

Jak wynika z powyższego rysunku, rozwiązania w transporcie mogą obejmować różne aspekty, w tym infrastrukturę, systemy zarządzania, technologie oraz organizację procesów logistycznych. W literaturze można znaleźć wiele przykładów tego typu rozwiązań, a część z nich została już zaimplementowana do działalności transportowej i przyjęta w praktyce funkcjonowania sektora. Jednakże w dobie dynamicznego postępu technologicznego, gdzie coraz bardziej na znaczeniu zyskują sztuczna inteligencja (*ang. Artificial Intelligence*), zaawansowane systemy automatyzacji, Internet Rzeczy (*ang. Internet of Things*) oraz technologie oparte na Big Data, pojawianie się kolejnych innowacji jest zjawiskiem nieuniknionym. Nowoczesne rozwiązania, jak autonomiczne pojazdy, bezzałogowe statki powietrzne czy inteligentne systemy zarządzania ruchem wciąż zmieniają oblicze sektora transportu, czyniąc go bardziej efektywnym, bezpiecznym i ekologicznym. Przeprowadzony w publikacji **P1** przegląd literatury, obejmujący analizę ponad 220 źródeł, pozwolił zidentyfikować rozwiązania istotne z punktu widzenia kształtowania odporności sektora, a w efekcie ważne dla gospodarki jako całości, szczególnie wobec współczesnych kryzysów. Wyniki tego badania wpisują się w problematykę zrównoważonego rozwoju transportu poprzez wskazanie postępów i innowacji sprzyjających ograniczaniu emisji gazów cieplarnianych, poprawie efektywności energetycznej, podnoszeniu poziomu bezpieczeństwa oraz wzmacnianiu zdolności adaptacyjnych sektora transportu do zmieniających się uwarunkowań. Artykuł stanowi zatem praktyczną bazę dla decydentów, organizatorów oraz wykonawców przewozów dostarczając rekomendacji, które rozwiązania powinny być rozwijane i wdrażane, aby transport stawał się bardziej odporny, a jednocześnie przyjazny dla środowiska.

Podsumowując, w ramach badań ujętych w podrozdziale 3.1 nie tylko uporządkowano tło badawcze poprzez opracowanie typologii kryzysów istotnych z perspektywy transportu, ale przede wszystkim przeprowadzono analizę zależności zachodzących pomiędzy całkowitym wykorzystaniem energii końcowej w transporcie, emisjami CO_2 z działalności transportowej i dochodami budżetu państwa.

Odnosząc się do najważniejszych ustaleń należy wskazać, że transport pozostaje sektorem osadzonym w układzie długookresowych powiązań pomiędzy wymiarem energetycznym, emisyjnym i budżetowym. Przeprowadzone badania potwierdziły istnienie stabilnych długookresowych zależności pomiędzy zmiennymi TFECT, CO_2T i GREV, przy czym szczególną rolę w całym układzie odgrywało całkowite zużycie energii końcowej w transporcie. Zmienna TFECT okazała się głównym czynnikiem współkształtującym zarówno poziom emisji CO_2 transportu, jak i wielkość dochodów budżetu państwa, a zidentyfikowane zależności ujawniały się w sposób rozłożony w czasie. Z kolei opracowania uzupełniające, dotyczące rozwoju elektromobilności pokazały, że odpowiedź transportu na narastającą presję środowiskową wymaga nie tylko zmian regulacyjnych, ale również stopniowego wdrażania rozwiązań technologicznych i infrastrukturalnych. Wskazano, że pojazdy w pełni elektryczne sprzyjają trwałemu ograniczaniu presji emisyjnej, natomiast hybrydowe mogą pełnić istotną funkcję w okresie przejściowym, wspierając dostosowanie systemów transportowych do celów zrównoważonego rozwoju oraz ograniczanie zależności od paliw konwencjonalnych. Zaznaczono ponadto, że rzeczywista skala efektów środowiskowych elektromobilności pozostaje uzależniona od struktury wytwarzania energii elektrycznej, w tym od udziału OZE, co oznacza, że proces dekarbonizacji transportu powinien być rozpatrywany w powiązaniu z transformacją całego systemu energetycznego.

Przeprowadzone badania udzieliły odpowiedzi na problem szczegółowy **PS1** wskazując, że współczesne wyzwania środowiskowe i gospodarcze determinują funkcjonowanie transportu w Polsce przede wszystkim poprzez długookresową presję dostosowawczą obejmującą zużycie energii, emisyjność oraz warunki ekonomiczne. Oznacza to, że rozwój transportu nie może być rozpatrywany niezależnie od czynników środowiskowych, polityki fiskalnej i kierunków przemian technologicznych. W świetle uzyskanych wyników można potwierdzić hipotezę szczegółową **HS1**. Przeprowadzone analizy dowiodły istnienia stabilnych relacji długookresowych w układzie całkowite wykorzystanie energii końcowej w transporcie – emisje dwutlenku węgla pochodzące z działalności transportowej – dochody budżetu państwa. Pozwoliły również określić charakter ich wzajemnych oddziaływań w czasie. Zidentyfikowane zależności pokazały, że wzrost zużycia energii końcowej w transporcie wiąże się ze wzrostem emisji CO_2 z transportu i wpływa na poziom dochodów budżetu państwa. Zatem zmiany w jednym obszarze przekładają się na pozostałe, tworząc układ powiązań określających uwarunkowania dla transportu.

Powyższe wnioski są znaczące dla całości rozprawy. Po pierwsze wyznaczają ramy i kierunki realizacji badań dzięki opracowanej typologii współczesnych kryzysów, co umożliwia analizowanie procesów transportowych stosownie do charakteru zjawiska. Co jednak istotniejsze to pokazano, że współczesne wyzwania środowiskowe i gospodarcze nie stanowią jedynie ogólnego kontekstu funkcjonowania transportu, lecz tworzą rzeczywisty układ presji, zależności i ograniczeń wpływających na jego obecną kondycję oraz dalsze możliwości rozwoju. Na tym tle ustalenia objęły również wskazanie możliwych kierunków działań sprzyjających zrównoważonym zmianom w sektorze. Jednocześnie należy zaznaczyć, że transport wciąż pozostaje narażony na nagłe zdarzenia i ich następstwa. Dlatego w kolejnym podrozdziale pracy skoncentrowano się na zakłóceniach o bardziej gwałtownym przebiegu odnosząc się do kryzysu zdrowotnego.

3.2. Funkcjonowanie transportu w warunkach kryzysu zdrowotnego [publikacje P3–P4]

Kryzysy zdrowotne związane z rozprzestrzenianiem się chorób zakaźnych mają odmienną skalę oddziaływania przestrzennego i pojawiają się w sposób nieregularny oraz zróżnicowany pod względem intensywności. Ich nagły i trudny do przewidzenia charakter sprawia, że towarzyszy im wysoki poziom niepewności oraz ograniczone możliwości wcześniejszego przygotowania się na ich wystąpienie. Zjawiska te przyjmują postać zarówno lokalnych ognisk chorób zakaźnych, jak również zagrożeń o wymiarze globalnym, czego przykładami są m.in. epidemie wirusa Ebola, ogniska SARS i MERS, pandemia grypy A/H1N1v oraz pandemia COVID-19 [73]. Spośród wymienionych zjawisk to właśnie ostatnie z nich stanowi najbardziej aktualny i kompleksowy przykład, umożliwiający szczegółową analizę oddziaływania kryzysu zdrowotnego na funkcjonowanie transportu [78, 79].

Pandemia COVID-19, która wybuchła w 2020 roku, w szybkim tempie zmieniła otoczenie społeczno-gospodarcze na całym świecie. Obowiązujące wówczas blokady (lockdowny) oraz wytyczne sanitarne, ukierunkowane na ograniczanie rozprzestrzeniania się wirusa SARS-CoV-2, miały wyraźne przełożenie na sposób funkcjonowania społeczeństwa, w tym na realizację codziennych czynności, organizację pracy i edukacji oraz aktywność gospodarczą [80]. Wprowadzane liczne restrykcje obejmujące m.in. ograniczenia mobilności, czasowe zamknięcie ruchu transgranicznego oraz częściowe wstrzymanie działalności handlowo-usługowej, oddziaływały na wiele sektorów gospodarki, nie pomijając przy tym transportu [81]. Polska, jako integralna część europejskiej sieci transportowej, również odczuła skutki tego kryzysu zdrowotnego w obszarze organizacji i realizacji przewozów.

W publikacji **U4** przeanalizowano wpływ pandemii COVID-19 na sektor transportu w Polsce, stosując trójstopniową skalę oceny poziomu oddziaływania zagrożenia w kolejnych fazach jego rozwoju. Badanie umożliwiło identyfikację obszarów najbardziej podatnych na zakłócenia w transporcie pasażerskim i towarowym z uwzględnieniem podziału na gałęzie lądową, morską i powietrzną. Wskazano, że wyraźnie większe zakłócenia odnotowano w przypadku przewozów pasażerskich, co wynikało z obowiązujących restrykcji mobilności, limitów liczby pasażerów w środkach transportu zbiorowego oraz wzmożonych obaw ludności o zdrowie i życie. Spośród rozpatrywanych gałęzi najbardziej dotknięty skutkami pandemii był pasażerski transport powietrzny, przede wszystkim z powodu ograniczeń w ruchu międzynarodowym oraz szczególnych wymagań dotyczących przekraczania granic państwowych, co przełożyło się na znaczący spadek popytu na zagraniczne podróże. Restrykcje w przewozach międzynarodowych wpłynęły również na ograniczenie aktywności pasażerskiego transportu wodnego, w tym rejsów wycieczkowych i przepraw promowych. Negatywne konsekwencje pandemii objęły także pasażerski transport lądowy, głównie z powodu limitów przewozowych i obniżonego poczucia bezpieczeństwa wśród podróżnych, przy czym po złagodzeniu obostrzeń zaobserwowano stopniową odbudowę popytu w ruchu krajowym. Transport towarowy doświadczył relatywnie mniejszego wpływu pandemii, a poziom zakłóceń był porównywalny we wszystkich gałęziach. Największe trudności występowały w początkowych fazach rozwoju zagrożenia epidemicznego i dotyczyły m.in. problemów w krajowych i globalnych łańcuchach dostaw, wzrostu kosztów operacyjnych oraz zmian w strukturze przewożonych ładunków. Przedstawione wyniki wskazują, że szczególnym obszarem oddziaływania pandemii był transport pasażerski, którego funkcjonowanie było silnie zależne od zmian w mobilności ludności kształtowanych przez obowiązujące restrykcje, zwłaszcza w ruchu międzynarodowym. W tym kontekście zasadne stało się ukierunkowanie analiz na powiązania pomiędzy popytem na przewozy pasażerskie, a ruchem turystycznym, które w okresie pandemii uległy poważnym zaburzeniom.

Artykuł **U5** obejmował analizę powiązań pomiędzy zmianami aktywności turystycznej a funkcjonowaniem pasażerskiego transportu w Polsce. Zakres czasowy badania obejmował lata 2017–2021, dzięki czemu możliwe było porównanie warunków względnie stabilnych z okresem gwałtownego zaburzenia na skutek zagrożenia epidemicznego. W celu określenia kierunku zmian w analizowanych szeregach czasowych zastosowano metodę wygładzania z wykorzystaniem prostej średniej ruchomej, pozwalającą ograniczyć występujące krótkookresowe wahania i zidentyfikować ogólne tendencje. Przeprowadzona analiza wskazała na wyraźne osłabienie aktywności turystycznej w okresie pandemii, przy czym skala zmian różniła się pomiędzy wyjazdami krajowymi i zagranicznymi. Najistotniejsze ograniczenia dotyczyły mobilności międzynarodowej, co przełożyło się zmniejszenie liczby podróży zagranicznych, podczas gdy ruch krajowy wykazywał relatywnie niższy poziom spadków oraz wcześniejsze oznaki stabilizacji po częściowym znoszeniu restrykcji.

Zróżnicowanie to znalazło odzwierciedlenie w liczbie pasażerów w podziale na poszczególne gałęzie transportu. Analiza wyznaczonych trendów wykazała, że najsilniejsze zakłócenia wystąpiły w pasażerskim transporcie powietrznym, którego prawidłowe funkcjonowanie jest w głównej mierze uzależnione od ruchu transgranicznego. Wyraźne spadki liczby pasażerów odnotowano również w transporcie drogowym. Relatywnie mniejsze zmiany nastąpiły natomiast w przypadku transportu kolejowego, morskiego oraz wodnego śródlądowego, co uwidacznia zróżnicowanie oddziaływania pandemii COVID-19 pomiędzy poszczególnymi gałęziami.

Uzyskane w tym badaniu wyniki pokazały, że zakres i skala zaburzeń w funkcjonowaniu transportu pasażerskiego były silnie uzależnione od stopnia powiązania danej gałęzi z ruchem międzynarodowym, a tym samym od struktury popytu turystycznego, która w okresie pandemii uległa istotnym przekształceniom. Szczególnego znaczenia w tym ujęciu nabiera pasażerski transport powietrzny, który w warunkach kryzysu zdrowotnego okazał się najbardziej wrażliwy na wprowadzane restrykcje. Dlatego w kolejnym etapie badań skoncentrowano się na polskim lotnictwie pasażerskim podczas pandemii oraz w fazie odbudowy po jej ustąpieniu.

W publikacji **P3** przeprowadzono analizę porównawczą kondycji pasażerskiego transportu powietrznego w Polsce oraz w wybranych krajach europejskich w sytuacji zakłócenia pandemią COVID-19. Badaniem objęto okres od stycznia 2004 do marca 2024, gdyż tylko dla tego przedziału czasowego dostępny był kompletny ciąg obserwacji miesięcznych dla wszystkich 30 państw. Spośród zestawu danych dokonano selekcji rynków, których charakterystyka przewozowa w latach poprzedzających wystąpienie zagrożenia epidemicznego w największym stopniu odpowiadała wartościom obserwowanym dla rynku polskiego. W rezultacie, obok Polski, w zestawieniu uwzględniono Portugalię, Szwecję, Norwegię oraz Szwajcarię. Z wyekstrahowanych w ten sposób danych utworzono szeregi czasowe liczby przewożonych pasażerów w poszczególnych państwach, z których każdy został podzielony na dwa zbiory przyjmując za moment rozdzielenia wybuch pandemii COVID-19 w marcu 2020 r. Pierwszy z nich posłużył do opracowania modelu matematycznego oraz wyznaczenia prognoz na okres po wystąpieniu zagrożenia epidemicznego. Drugi stanowił zbiór referencyjny, pozwalający na ocenę strat poprzez porównanie stanu rzeczywistego (odzwierciedlającego spadki wywołane pandemią) z prognozami opartymi na wynikach sprzed marca 2020, które wskazywały potencjalny (referencyjny) poziom przewozów w przypadku braku wystąpienia zakłóceń.

Zasadniczy element badania stanowiło modelowanie matematyczne liczby pasażerów w transporcie powietrznym, które umożliwiło analizę zmian zachodzących w wynikach przewozowych na wybranych rynkach krajowych wywołanych nagłym kryzysem zdrowotnym. Dzięki zastosowaniu modelu wygładzania wykładniczego Holta–Wintersa, na podstawie wyników sprzed pandemii COVID-19, wyznaczono prognozy, które określały potencjalny poziom przewozów w przypadku braku wystąpienia zagrożenia epidemicznego. Dla każdego z rynków zastosowano wariant multiplikatywny modelu, pozwalający uchwycić zarówno tendencje rozwojowe, jak i wyraźną sezonowość charakterystyczną dla pasażerskiego rynku lotniczego. Współczynniki wygładzania wykładniczego poziomu (α), trendu (δ) oraz sezonowości (γ) dobierano tak, aby osiągnąć wysokie dopasowanie modelu do rzeczywistych danych poprzez minimalizację średniego bezwzględnego błędu procentowego. Po estymacji modeli dokonano ich szczegółowej oceny mającej na celu weryfikację jakości dopasowania do danych oraz poprawności przyjętych założeń statystycznych. W tym celu, poza błędem MAPE, obliczono wartości innych metryk takich jak ME, MAE oraz RMSE. Uzupełniająco obliczono współczynnik determinacji (R^2) jako pomocniczą miarę ogólnego dopasowania modelu. W ramach walidacji modeli zastosowano również kryterium informacyjne AIC, uwzględniające relację pomiędzy jakością dopasowania a złożonością parametryczną, oraz przeprowadzono test normalności Shapiro–Wilka, aby ocenić własności rozkładu reszt. Wartości współczynników wygładzania wykładniczego, metryk błędów oraz wybranych statystyk dla modeli opracowanych dla analizowanych rynków zestawiono w tabeli 3.2.1.

Tabela 3.2.1. Parametry opracowanych modeli Holta–Wintersa oraz wartości metryk błędów i wybranych statystyk

Kraj	**Parametry modelu**			**Metryki błędów**				**R^2**	**AIC**	**Test Shapiro–Wilka**
	α	***δ***	***γ***	**MAPE [%]**	**ME**	**MAE**	**RMSE**			***W (p-value)***
POLSKA	0,9	0,1	0,1	1,85	−298	45574	59391	0,99	24667	0,98 (0,11)
PORTUGALIA	0,8	0,1	0,1	1,97	594	67858	91947	0,99	2552	0,98 (0,18)
SZWECJA	0,6	0,1	0,1	1,64	−4088	47545	60790	0,98	2471	0,99 (0,36)
NORWEGIA	0,3	0,1	0,1	1,31	−598	40308	52653	0,99	2443	0,99 (0,51)
SZWAJCARIA	0,4	0,1	0,1	1,43	−3300	58235	73840	0,99	2509	0,98 (0,18)

Jak pokazują wyniki zestawione w powyższej tabeli, zastosowane wygładzanie wykładnicze Holta–Wintersa okazało się skuteczne w modelowaniu liczby pasażerów na wybranych rynkach lotniczych zakłóconych wybuchem pandemii COVID-19. Potwierdzają to niskie wartości błędów prognoz, w tym wartości MAPE nieprzekraczające 2% we wszystkich analizowanych przypadkach. Ponadto wartości współczynnika R^2 każdorazowo przekraczały 0,98, co potwierdza bardzo wysoką jakość dopasowania modeli do danych obserwowanych. Prognozy uzyskane z modeli posłużyły następnie do oszacowania strat liczby przewiezionych pasażerów (L_m) oraz stopnia osiągnięcia referencyjnego poziomu przewozów (R_m) w kolejnych przedziałach czasowych (m) po wybuchu pandemii COVID-19. Uzyskane wyniki dla wszystkich rozpatrywanych rynków krajowych przedstawiono w tabeli 3.2.2.

Tabela 3.2.2. Straty związane z pandemią i stopień osiągnięcia poziomu referencyjnego oszacowane na podstawie prognoz z modeli

KRAJ	**Okres po wybuchu pandemii COVID-19**									
	3 miesiące (*m = 3*)		**6 miesięcy (*m = 6*)**		**12 miesięcy (*m = 12*)**		**18 miesięcy (*m = 18*)**		**24 miesiące (*m = 24*)**	
	***Lm*[b]**	***Rm [%]***	***Lm*[b]**	***Rm [%]***	***Lm*[b]**	***Rm [%]***	***Lm*[b]**	***Rm [%]***	***Lm*[b]**	***Rm [%]***
POLSKA	10,91	10,16	24,43	15,25	44,45	15,42	66,77	20,38	79,84	27,11
PORTUGALIA	13,54	12,54	30,53	14,85	53,87	16,34	84,50	19,18	100,07	26,62
SZWECJA	7,82	14,34	16,93	12,82	30,84	13,86	45,03	17,34	52,94	24,59
NORWEGIA	8,22	18,83	17,53	21,16	32,88	20,56	50,09	21,83	59,03	29,34
SZWAJCARIA	12,64	12,93	25,73	16,41	48,45	15,43	70,83	19,72	83,86	27,01

[b] w milionach przewiezionych pasażerów.

Dodatkowo, rzeczywiste wyniki przewozowe w kolejnych miesiącach po wybuchu pandemii porównano z danymi ze stycznia 2020, co pozwoliło ocenić tempo odbudowy rynków pasażerskich przewozów lotniczych w wybranych państwach Europy.

Uzyskane wyniki wykazały, że pandemia COVID-19 spowodowała we wszystkich analizowanych krajach gwałtowny spadek liczby pasażerów w transporcie lotniczym, przy czym skala poniesionych strat, stopień osiągniecia poziomu referencyjnego oraz tempo odbudowy różniły się znacząco pomiędzy rynkami. W pierwszych miesiącach pandemii największego deficytu liczby obsługiwanych pasażerów doświadczyły Portugalia i Szwajcaria, czyli państwa bardziej uzależnione od ruchu międzynarodowego i turystycznego. Relatywnie mniejsze straty odnotowano natomiast w Norwegii i Szwecji, gdzie znaczącą rolę odgrywają połączenia krajowe. Zróżnicowanie to utrzymywało się również w kolejnych przedziałach czasowych.

Polska, podobnie jak inne kraje z zestawienia, doświadczyła poważnego załamania ruchu pasażerskiego w początkowej fazie pandemii. Jednocześnie stopień osiągnięcia poziomu referencyjnego i tempo odbudowy w kolejnych latach okazały się zbliżone do tych widocznych w silniejszych, europejskich gospodarkach. Szczególnie od 2022 r. obserwowano stopniowe odtwarzanie sezonowego wzorca ruchu pasażerskiego oraz osiąganie poziomów przewozów przekraczających wartości ze stycznia 2020 r. Warto zaznaczyć, że pomimo silnego załamania popytu na początku pandemii, polski rynek wykazał zdolność do relatywnie szybkiego zbliżania się do prognozowanego poziomu przewozów, osiągając najwyższy przyrost wskaźnika R_m w całym zestawieniu (+16,95 pp.). W efekcie w drugim roku po wystąpieniu zagrożenia Polska znajdowała się wśród rynków o najwyższym stopniu osiągnięcia poziomu zakładającego brak pandemii.

Analiza porównawcza potwierdza, że rynki o większym udziale przewozów krajowych charakteryzowały się wyższą odpornością na ograniczenia mobilności międzynarodowej, podczas gdy rynki skoncentrowane na ruchu międzynarodowym doświadczały głębszych i dłużej utrzymujących się spadków. Otrzymane wyniki pozwoliły zidentyfikować reakcje pasażerskiego lotnictwa na kryzysy zdrowotne obejmujące skalę załamania popytu, stopień osiągnięcia referencyjnego poziomu przewozów oraz tempo powrotu do stanu sprzed wystąpienia zakłóceń. Z perspektywy odporności pasażerskiego transportu powietrznego oznacza to, że zdolność do adaptacji w warunkach kryzysu zdrowotnego nie jest determinowana wyłącznie wielkością rynku, lecz w dużym stopniu zależy od struktury przewozów. Biorąc pod uwagę wzorce odporności zaobserwowane na rozpatrywanych rynkach, z rezultatów analizy porównawczej wynikają praktyczne kierunki działań dla organów odpowiedzialnych za kształtowanie polityki transportowej i podmiotów sektora lotniczego:

- Utrzymywanie minimalnej, strategicznej siatki połączeń krajowych w celu zwiększenia odporności rynku lotniczego na przyszłe kryzysy o podłożu epidemicznym. W warunkach Polski nie oznacza to rozbudowy pełnej sieci krajowej na wzór państw o silnie rozwiniętym ruchu wewnętrznym (np. Norwegia, Szwecja), lecz utrzymanie tych połączeń, które mogą pełnić funkcję stabilizującą w sytuacji czasowego ograniczenia ruchu zagranicznego, co pozwoli ograniczyć skalę spadku przewozów w początkowej fazie kryzysu.
- Planowanie rozwoju infrastruktury lotniczej w Polsce powinno uwzględniać utrzymywanie rezerwy przepustowości oraz możliwość szybkiego zwiększenia liczby operacji po wygaszeniu kryzysu zdrowotnego. Po okresie ograniczeń może pojawić się odroczony popyt, którego obsługa wymaga odpowiedniej liczby slotów, stanowisk postojowych, przepustowości terminali i personelu. Jednym z możliwych instrumentów realizacji tego celu może być rozwój nowych inwestycji infrastrukturalnych (np. CPK).
- Linie i porty lotnicze powinny opracować scenariusze szybkiego odtwarzania segmentów ruchu sezonowego, w szczególności turystycznego oraz VFR, które mogą odgrywać istotną rolę w odbudowie rynku po zniesieniu restrykcji mobilności. Oznacza to potrzebę wcześniejszego przygotowania procedur dotyczących przywracania oferty przewozowej oraz jej dostosowania do przewidywanej struktury popytu, co pozwoli skrócić czas odbudowy rynku po wystąpieniu kolejnego kryzysu o podobnej charakterystyce.
- Strategie rozwoju portów lotniczych i przewoźników powinny uwzględniać zróżnicowaną strukturę przewozów, obejmującą jednocześnie ruch biznesowy, turystyczny, VFR oraz segment przewoźników niskokosztowych, zamiast opierać funkcjonowanie rynku głównie na jednym rodzaju popytu. Ograniczenie zależności od pojedynczego segmentu podróży zwiększy odporność rynku na zakłócenia obejmujące wybrane kategorie przewozów oraz pozwoli utrzymać część ruchu pasażerskiego również w warunkach czasowego ograniczenia określonych rodzajów podróży.

Publikacja **P3** uwydatnia rolę modelowania matematycznego w badaniach dotyczących funkcjonowania procesów transportowych w warunkach kryzysów zdrowotnych. Zastosowanie modeli szeregów czasowych, a konkretnie wygładzania wykładniczego Holta–Wintersa w wariancie multiplikatywnym, posłużyło do wyznaczenia prognozowanego poziomu przewozów pasażerskich w przypadku braku wystąpienia zagrożenia.

Na tej podstawie oszacowano skalę poniesionych strat oraz stopień osiągnięcia poziomu referencyjnego. Istotnym aspektem przyjętego w artykule podejścia było wykorzystanie jednolitej procedury modelowania dla wszystkich rozpatrywanych państw, co zapewniło porównywalność uzyskanych wyników. W efekcie modelowanie matematyczne stanowiło podstawę porównawczej analizy wpływu kryzysu zdrowotnego na funkcjonowanie pasażerskiego transportu lotniczego w wybranych krajach Europy, umożliwiając ocenę kondycji polskiego rynku na tle innych państw oraz identyfikację zróżnicowanych reakcji poszczególnych rynków na występujące wówczas zakłócenia.

W dalszej części badań skupiono się na przepływie pasażerów w transporcie morskim. W artykule **P4** opracowano modele matematyczne umożliwiające ocenę wpływu pandemii COVID-19 na ten ruch. Badanie oparto na kwartalnych danych dotyczących całkowitej liczby pasażerów w portach morskich w Polsce w latach 2004–2023, oceniając w pierwszej kolejności zmienność oraz sezonowość tego szeregu z wykorzystaniem podstawowych miar położenia i rozproszenia. Analiza rozkładów rocznych wskazała na systematyczny wzrost mediany liczby pasażerów w latach 2014–2019, po którym nastąpiło wyraźne załamanie w latach 2020–2021, związane z wybuchem pandemii oraz wprowadzonymi ograniczeniami mobilności. Z kolei ujęcie kwartalne jednoznacznie potwierdziło występowanie silnej sezonowości ruchu pasażerskiego. Najwyższą medianę liczby pasażerów obserwowano w trzecim kwartale (powyżej 750 tys.), który charakteryzował się również największym rozstępem międzykwartylowym, co wskazywało na dużą zmienność ruchu w szczycie sezonu letniego.

Następny etap badania obejmował opracowanie modeli matematycznych opisujących liczbę pasażerów w polskich portach morskich. Szereg czasowy tej zmiennej podzielono na zbiór treningowy i testowy, przyjmując za moment rozdzielenia IV kwartał 2022 r. Pierwszy zbiór wykorzystano do estymacji parametrów modeli i wyznaczenia prognoz, natomiast drugi do oceny ich dokładności. W publikacji rozpatrzono trzy modele. Pierwszym był SARIMA, stanowiący sezonowe rozszerzenie modelu ARIMA i umożliwiający jednoczesne modelowanie zależności autoregresyjnych, składnika średniej ruchomej oraz regularnych wahań sezonowych w szeregu czasowym. Kolejnym był model Holta–Wintersa, opisujący szereg czasowy za pomocą trzech równań wygładzania odpowiadających poziomowi, trendowi oraz sezonowości. W tym przypadku zastosowano jego wariant multiplikatywny, w którym wahania sezonowe zmieniają się proporcjonalnie do poziomu szeregu. Ostatni z zaproponowanych to model STL oparty na dekompozycji szeregu czasowego na składowe trendu, sezonowości i składnik resztowy, których wartości wyznaczane są z wykorzystaniem wygładzania LOESS. Selekcję specyfikacji modeli w ramach poszczególnych typów przeprowadzono na podstawie kryteriów informacyjnych AIC i BIC. Parametry modeli SARIMA i Holta–Wintersa oraz statystyki komponentów dekompozycji STL przedstawiono w tabeli 3.2.3.

Tabela 3.2.3. Parametry i oceny komponentów opracowanych modeli

SARIMA (1,0,0)(0,1,1)$_4$			
Współczynnik		Wartość	Błąd standardowy
AR(1)		0,6488	0,1009
SMA(1)		−0,3189	0,1432
Holt-Winters multiplikatywny			
Współczynnik wygładzania wykładniczego		Wartość	
Poziomu *(α)*		0,3655	
Trendu *(β)*		0,0001	
Sezonowości *(γ)*		0,6344	
STL			
Komponent	Statystyka	Wartość	Udział w zmienności [%]
Sezonowość	IQR	214,73	78,4
	Mediana	−60,76	-
Trend	IQR	110,27	40,2
	Mediana	463,63	-
Składnik resztowy	IQR	37,92	13,8
	Mediana	−0,33	-

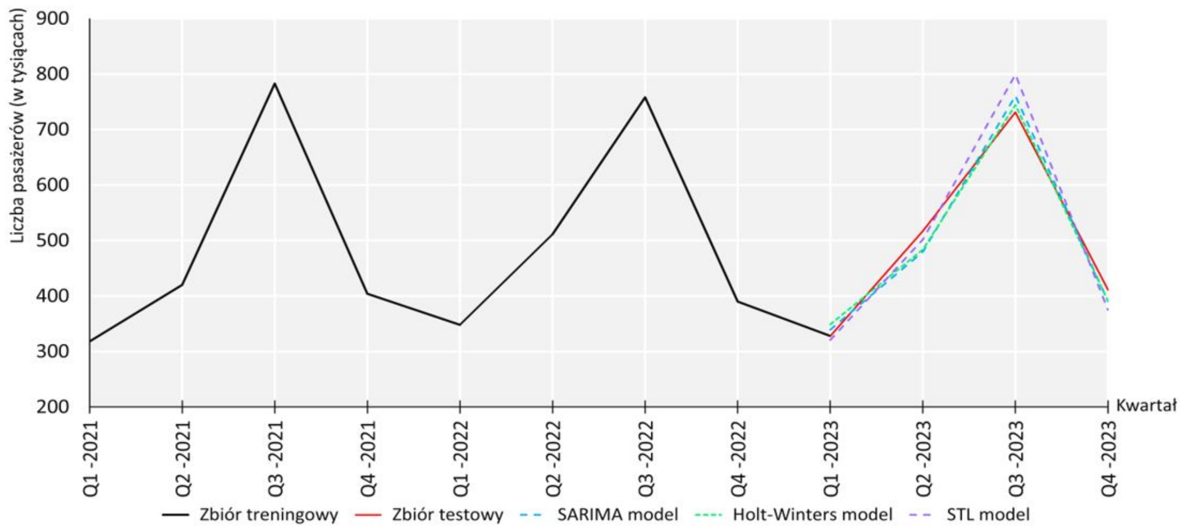
Dla każdego z modeli oceniono również dokładność wyznaczonych prognoz, obliczając wartości metryk błędów MAE, MSE i RMSE, które zestawiono w tabeli 3.2.4.

Tabela 3.2.4. Wartości metryk błędów dla opracowanych modeli

Model	**Metryki błędów**		
	MAE	**MSE**	**RMSE**
SARIMA (1,0,0)(0,1,1)$_4$	29,61	1004,55	31,69
Holt-Winters multiplikatywny	29,15	849,55	27,07
STL	28,84	1382,17	37,18

Najwyższą dokładność prognoz uzyskano dla modelu Holta–Wintersa, który osiągnął najniższe wartości MSE i RMSE. W przypadku modelu SARIMA błędy prognoz były również relatywnie niskie. Z kolei model STL, z wyjątkiem MAE, uzyskał wyższe wartości metryk.

W kolejnym etapie badania porównano wyniki otrzymane z zastosowaniem każdego z modeli. Porównanie prognoz względem zbioru testowego przedstawiono na rysunku 3.2.1.



Rys. 3.2.1. Porównanie prognoz liczby pasażerów uzyskanych z opracowanych modeli z wartościami rzeczywistymi (zbiór testowy)

Uzyskane wyniki pozwoliły zidentyfikować prawidłowości w kształtowaniu się liczby pasażerów w polskich portach morskich oraz ocenić możliwości analityczne trzech różnych modeli w ramach analizy i prognozowania tego zjawiska. Porównanie prognoz z wartościami rzeczywistymi dla poszczególnych kwartałów 2023 r. wskazuje, że w większości przypadków wartości prognozowane były wyższe od obserwowanych, z wyjątkiem II kwartału 2023 r., co potwierdza skalę następstw wcześniejszych zakłóceń wywołanych rozprzestrzenianiem się wirusa SARS-CoV-2. Z kolei analiza porównawcza zastosowanych modeli wskazuje na ich zróżnicowaną użyteczność w interpretacji i prognozowaniu liczby pasażerów w portach morskich. Jako model preferowany wskazano SARIMA, ponieważ obok stosunkowo wysokiej dokładności prognoz charakteryzował się najniższymi wartościami kryteriów informacyjnych. Zadowalające wyniki pod względem jakości prognoz uzyskano również w przypadku modelu Holta–Wintersa, który bardzo dobrze odwzorowywał zmiany liczby pasażerów. Model STL, choć charakteryzował się mniejszą dokładnością, odegrał istotną rolę interpretacyjną, ponieważ dekompozycja szeregu czasowego pozwoliła na indywidualne analizowanie jego składowych. W rezultacie zaobserwowano przede wszystkim wyraźną i stabilną sezonowość kwartalną ruchu pasażerskiego, utrzymującą się w całym badanym okresie. Oznacza to, że nawet tak silne zakłócenie jak pandemia COVID-19 nie doprowadziło do zmiany wzorca sezonowego zainteresowania rejsami morskimi. Skalę oddziaływania kryzysu zdrowotnego na poziom przewozów wyraźnie odzwierciedlał natomiast komponent trendu. Szczególnie widoczny spadek liczby pasażerów odnotowano w okresie od III kwartału 2019 r. do III kwartału 2020 r., co miało związek z ograniczeniami mobilności oraz spadkiem popytu na podróże międzynarodowe w tym czasie.

Artykuł **P4** podkreśla znaczenie modelowania matematycznego w analizie funkcjonowania pasażerskiego transportu morskiego w sytuacji kryzysu zdrowotnego. Zastosowanie trzech modeli o odmiennych założeniach umożliwiło zarówno wyznaczenie prognoz liczby pasażerów w polskich portach morskich, jak i porównanie zdolności tych modeli do odwzorowania zmian zachodzących w analizowanym szeregu czasowym. Dzięki zastosowanemu podejściu możliwe było zidentyfikowanie prawidłowości kształtujących morskie przewozy pasażerskie, w szczególności ich sezonowości kwartalnej, a także przeprowadzenie analizy zmian wynikających z oddziaływania czynników związanych z kryzysem o podłożu epidemicznym. Opracowane modele matematyczne można zatem traktować jako komplementarne w analizie zmian ruchu pasażerskiego w portach morskich, pozwalające zarówno oceniać skutki zdarzeń kryzysowych, jak i prognozować poziom przewozów pasażerskich. Uzyskane wyniki oraz analiza zastosowanych modeli pozwalają sformułować rekomendacje dla pasażerskiego transportu morskiego w obliczu kryzysów zdrowotnych:

- Wykorzystanie modelowania matematycznego w planowaniu działalności przewozowej przez operatorów pasażerskiego transportu morskiego powinno obejmować nie tylko prognozowanie liczby pasażerów, ale także bieżące analizowanie odchyleń pomiędzy wartościami prognozowanymi a rzeczywistymi. Umożliwi to wcześniejsze identyfikowanie oznak zakłóceń, a w efekcie będzie wspierać podejmowanie decyzji dotyczących liczby połączeń i wykorzystania floty w zmieniających się warunkach.
- Planowanie działalności przewozowej w pasażerskim transporcie morskim powinno uwzględniać, że w warunkach kryzysu o podłożu epidemicznym zachowaniu ulega sezonowy rozkład ruchu pasażerskiego, natomiast zmianie podlega poziom przewozów, odzwierciedlany przede wszystkim przez komponent trendu. Oznacza to konieczność dostosowywania liczby połączeń, wielkości eksploatowanej floty, przepustowości infrastruktury portowej oraz organizacji obsługi pasażerów nie tylko do utrzymującego się wzorca sezonowego, ale także do obniżonego poziomu popytu. Przyczyni się to do zwiększenia zgodności zdolności przewozowej z rzeczywistą skalą przewozów w okresie kryzysu, a tym samym ograniczy nadmiarową podaż usług transportowych i zmniejszy ryzyko niewykorzystania dostępnych zasobów.
- Rekomenduje się równoległe stosowanie modeli reprezentujących odmienne podejścia do analizy szeregów czasowych, ponieważ umożliwia to wieloaspektową ocenę zmian liczby pasażerów w warunkach zakłóceń. Wykorzystanie modeli komplementarnych pozwala na rozróżnienie wahań związanych z sezonowością od zmian o charakterze

długookresowym oraz odchyleń krótkookresowych, co ogranicza ryzyko błędnej interpretacji przyczyn zmian ruchu pasażerskiego.

Poza transportem powietrznym i morskim badano również aspekt funkcjonowania kolei w kontekście pandemii COVID-19. Dlatego w publikacji **U6** analizowano, jak długo utrzymywały się zakłócenia popytu na pasażerskie przewozy kolejowe, porównując prognozy oparte na danych sprzed pandemii z rzeczywistymi wynikami. Na tej podstawie oceniono, po jakim czasie rynek w Polsce pod względem liczby pasażerów osiągnął poziom możliwy do uzyskania w warunkach braku zagrożenia wirusem SARS-CoV-2.

Analizy rozpoczęto od przeprowadzenia testu stacjonarności ADF dla szeregu czasowego obejmującego okres przedpandemiczny. Wynik wskazał na brak stacjonarności szeregu, co stanowiło przesłankę do przeprowadzenia różnicowania i estymacji modeli klasy ARIMA. Według kryterium AIC najlepszy okazał się model ARIMA(0,1,1) z dryfem, jednak funkcja ACF reszt wykazała występowanie autokorelacji dla opóźnienia równego 12. W związku z tym uwzględniono komponent sezonowy i oszacowano model SARIMA$(0,1,0)(1,0,1)_{12}$, który charakteryzował się brakiem istotnych autokorelacji reszt oraz niższą wartością AIC. Ostatecznie model ten został wykorzystany do wyznaczenia prognozy pozwalającej określić potencjalny poziom przewozów pasażerskich w przypadku braku zakłóceń spowodowanych kryzysem zdrowotnym.

Rezultaty pokazały, że od połowy 2021 r. obserwacje zaczynały zawierać się w 95-procentowym przedziale ufności, co wskazuje na wygaszenie najgłębszej fazy zakłóceń popytowych. Od marca 2022 r. wartości rzeczywiste znacznie zbliżyły się do prognoz, jednakże wciąż pozostawały poniżej wyznaczonego poziomu. Dopiero od sierpnia 2023 r. widoczna była zbieżność obu szeregów, co świadczy o ustąpieniu zakłóceń w wynikach przewozowych [82].

Zastosowane modelowanie matematyczne pozwoliło na określenie skali załamania popytu spowodowanego pandemią oraz czasu potrzebnego do uzyskania przez rynek poziomu możliwego w sytuacji bez wystąpienia kryzysu. Wyniki potwierdzają, że pandemia znacząco zaburzyła pasażerskie przewozy kolejowe w Polsce, a proces powrotu rynku na ścieżkę rozwoju wyznaczoną przez model SARIMA miał charakter stopniowy i rozciągający się w czasie.

Zakres i trwałość analizowanych zakłóceń, a także czas wymagany do osiągnięcia wyników oczekiwanych w przypadku braku pandemii, uzasadniają potrzebę wskazania działań wzmacniających odporność transportu kolejowego na podobne zagrożenia w przyszłości:

- Wykorzystanie modeli matematycznych do prognozowania poziomu przewozów na podstawie danych sprzed wystąpienia kryzysu zdrowotnego jako narzędzia identyfikacji odchylenia rzeczywistego poziomu przewozów od poziomu referencyjnego, odpowiadającego warunkom niezakłóconego rozwoju rynku. Porównywanie rzeczywistych wyników z poziomem możliwym do osiągnięcia w przypadku braku zagrożenia powinno stanowić podstawę do oceny skali destabilizacji rynku oraz określania momentu stopniowego przywracania zawieszonych połączeń. Pozwoli to ograniczyć opóźnienia decyzyjne, trafniej dostosować podaż przewozów do rzeczywistego tempa odbudowy rynku oraz zwiększyć zdolność pasażerskiego transportu kolejowego do przechodzenia z fazy zakłócenia do fazy stabilizacji.

- Wdrożenie wielostopniowych procedur reagowania w pasażerskim transporcie kolejowym, odpowiadających poziomom zagrożenia epidemicznego. Dla każdego z nich powinny zostać określone: minimalna liczba połączeń, dopuszczalne napełnienie pociągów, zakres ograniczeń sanitarnych oraz sposób informowania pasażerów. Uporządkuje to proces podejmowania decyzji w warunkach kryzysu, a tym samym pozwoli ograniczyć ryzyko nadmiernych lub opóźnionych reakcji organizacyjnych.
- Projektowanie nowych wagonów osobowych i modernizacja będących w eksploatacji w sposób umożliwiający szybkie dostosowanie układu wnętrza do zmieniających się wymogów sanitarnych (np. czasowe wyłączenie części miejsc, stosowanie modułowych stref siedzących). Rozwiązanie to powinno zwiększać zdolność pasażerskiego transportu kolejowego do funkcjonowania w warunkach zredukowanej dopuszczalnej liczby pasażerów, bez konieczności proporcjonalnego ograniczania realizowanych przewozów. W efekcie tabor nie będzie stanowił wyłącznie elementu podporządkowanego restrykcjom mobilności, lecz zostanie wykorzystany jako narzędzie adaptacji organizacji przewozów kolejowych do zmienionych warunków funkcjonowania transportu.

Dodatkowo prowadzono badania dotyczące funkcjonowania transportu pasażerskiego w warunkach kryzysu zdrowotnego, które zawężono do systemu komunikacji miejskiej, opierając się na przykładzie aglomeracji warszawskiej. Artykuł **U7** uwydatnia, że wybuch pandemii COVID-19 radykalnie zmienił sposób postrzegania transportu publicznego, który został wówczas zidentyfikowany jako jeden z głównych wektorów rozprzestrzeniania się wirusa na gęsto zaludnionych obszarach, co doprowadziło do spadku zainteresowania przewozami zbiorowymi. W badaniu wykorzystano dane dotyczące realizacji przewozów pasażerskich w warszawskim transporcie publicznym w latach 2019–2022. Na ich podstawie utworzono szeregi czasowe obejmujące okres przedpandemiczny oraz okres po wybuchu pandemii COVID-19. Przygotowane w ten sposób szeregi poddano wygładzaniu wykładniczemu metodą Browna, opartą na jednym parametrze wygładzania (α), oraz metodą

Holta, w której stosuje się parametry wygładzania poziomu (α) oraz trendu (β). W obu metodach parametry α, β dobrano tak, aby uzyskać wysokie dopasowanie modelu do rzeczywistych danych poprzez minimalizację błędów MAPE i RMSE. Następnie określono kierunki zmian w poszczególnych okresach wyznaczając trend liniowy na podstawie prognozowanych wartości.

Uzyskane wyniki wskazują, że wybuch pandemii COVID-19 istotnie wpłynął na funkcjonowanie warszawskiego transportu publicznego, co potwierdzają fluktuacje wskaźników opisujących realizację procesów transportowych, takich jak wykonana praca przewozowa, liczba przewiezionych pasażerów oraz liczba sprzedanych biletów. W okresie pandemii nastąpiła zmiana kierunku trendu pracy przewozowej. Odnotowano spadek o około 15,14 tys. wozokilometrów miesięcznie, co wskazuje na ograniczenie podaży usług przewozowych przez operatorów. Z kolei analiza liczby przewiezionych pasażerów wykazała wyraźną tendencję spadkową od momentu wystąpienia kryzysu. Tempo zmian wynosiło około −102,96 mln osób rocznie, co było przede wszystkim konsekwencją obowiązujących wówczas ograniczeń mobilności. Poza tym całkowita sprzedaż biletów zmalała z 7,08 mln w 2019 r. do 4,88 mln w 2020 r., a w okresie marzec–czerwiec 2020 r. w strukturze sprzedaży zmniejszył się udział biletów krótko- i długoterminowych [83].

W badaniu tym modelowanie matematyczne umożliwiło wyznaczenie trendów w analizowanych szeregach czasowych przy jednoczesnym ograniczeniu wpływu krótkookresowych wahań. Pozwoliło to na określenie kierunku i tempa zmian wskaźników opisujących funkcjonowanie transportu publicznego, identyfikację momentów przełomowych w realizacji procesów transportowych oraz oszacowanie skali oddziaływania pandemii COVID-19 na system warszawskiej komunikacji miejskiej. W konsekwencji przeprowadzonych analiz sformułowano także rekomendacje ukierunkowane na kształtowanie odporności systemu transportu publicznego na potencjalne kryzysy o podłożu epidemicznym. Wśród nich można wskazać:

- Struktura sprzedaży biletów w miejskim transporcie publicznym powinna stanowić istotny element monitorowania zmian potrzeb przewozowych w warunkach kryzysu zdrowotnego. Odchylenia od typowego udziału poszczególnych rodzajów biletów mogą wskazywać na zmianę sposobu korzystania z transportu publicznego, związaną z ograniczeniem regularnych podróży oraz zmianą postrzegania bezpieczeństwa korzystania ze zbiorowych środków transportu przez pasażerów. Zaobserwowane zmiany mogą stanowić wskazanie do właściwego kształtowania podaży usług transportowych i polityki taryfowej, co pozwoli lepiej dostosować funkcjonowanie systemu transportu miejskiego do zmieniających się potrzeb przewozowych oraz ograniczyć skutki popytowe i finansowe kryzysu.

- Ograniczenia podaży usług transportowych w aglomeracji miejskiej w warunkach kryzysu o podłożu epidemicznym nie powinny być wprowadzane w jednakowym stopniu we wszystkich środkach transportu. Zakres ograniczeń powinien uwzględniać zarówno zmiany liczby pasażerów i pracy przewozowej w całym systemie transportu publicznego, jak i znaczenie poszczególnych środków transportu dla realizacji przewozów. W pierwszej kolejności powinien on obejmować środki o najmniejszym udziale w przewozach, tj. kolej dojazdową i aglomeracyjną, przy jednoczesnym utrzymaniu możliwie stabilnego poziomu funkcjonowania komunikacji autobusowej, tramwajowej i metra, stanowiących podstawę obsługi przewozowej. Pozwoli to zachować ciągłość najważniejszych relacji komunikacyjnych oraz ograniczyć koszty funkcjonowania systemu bez istotnego pogorszenia dostępności transportu.

Wyniki i wnioski otrzymane w drodze opracowania artykułu **U7** stanowiły punkt wyjścia do rozszerzenia rozważań o ocenę dostępnych w aglomeracji warszawskiej środków transportu pod kątem zapewnienia bezpieczeństwa pasażerom w warunkach zagrożenia epidemicznego. W efekcie powstała publikacja **U8**, w której rozpatrzono trzy scenariusze uwzględniające strukturę demograficzną miasta i specyficzne potrzeby mieszkańców zaliczanych do konkretnych grup wiekowych. Ocenie poddano prywatne, publiczne i alternatywne środki transportu. Dla każdego ze scenariuszy wskazano wariant, który nie tylko zapewnia możliwie wysoki poziom bezpieczeństwa w warunkach zagrożenia epidemicznego, ale jest również optymalny pod względem czasu i kosztu podróży, komfortu oraz dostępności. W badaniu zastosowano metodę Bellingera pozwalającą na określenie łącznej oceny wariantów na podstawie przyjętych kryteriów cząstkowych oraz ich hierarchizację w poszczególnych scenariuszach. Otrzymane wyniki wskazują, że najbardziej bezpieczne i optymalne pod względem przyjętych kryteriów są indywidualne środki transportu. Transport publiczny, mimo swojej dostępności i niskich kosztów, wiąże się z wyższym ryzykiem zakażenia, co przełożyło się na jego niższą ocenę. W przypadku młodych osób najlepszym wyborem okazały się taksówki na żądanie oraz prywatne rowery, natomiast dla osób aktywnych zawodowo i seniorów najwyższe wyniki osiągnęły prywatne samochody. Poza tym dla starszych mieszkańców rozsądne alternatywy stanowiły również car-sharing i taksówki [84]. Badanie to przede wszystkim dostarcza informacji dotyczących optymalnych wyborów środków transportu w warunkach kryzysu zdrowotnego. Ponadto podkreśla, że istnieje potrzeba dostosowania miejskiej infrastruktury transportowej do potrzeb różnych grup użytkowników, co jest istotne nie tylko z perspektywy rozwoju obszarów zurbanizowanych, ale także ze względu na ryzyko kolejnych zagrożeń o podłożu epidemicznym w przyszłości.

Konkludując, niniejszy podrozdział dotyczył funkcjonowania pasażerskiego transportu w warunkach kryzysu zdrowotnego, rozpatrywanego w ramach pandemii COVID-19, którą uznano za najbardziej aktualny i kompleksowy przykład zagrożenia epidemicznego. Wyniki badań pokazały przede wszystkim, że zdarzenie to doprowadziło do poważnych a zarazem utrzymujących się zaburzeń w przewozach pasażerskich w Polsce, przy czym nie były one jednakowe we wszystkich gałęziach. Najsilniejsze zakłócenia wystąpiły w pasażerskim transporcie powietrznym, a skala odnotowanych strat oraz dynamika osiągania poziomów referencyjnych były zróżnicowane w zależności od struktury rynku i stopnia uzależnienia od ruchu międzynarodowego. W Polsce, po początkowym silnym załamaniu, nastąpił relatywnie szybki powrót do poziomów sprzed pandemii. Równocześnie obserwowano stopniowe zbliżanie się do scenariusza referencyjnego zakładającego brak zagrożenia. Warto podkreślić, że było to porównywalne ze wzorcami widocznymi w silniejszych gospodarkach europejskich. Z kolei w transporcie morskim wykazano, że w związku z wybuchem pandemii COVID-19 wzorce sezonowe ruchu pasażerskiego pozostały zachowane, ale zaobserwowano wyraźne zaburzenie trendu. Od marca 2020 r. liczba pasażerów istotnie się obniżyła, a skutki kryzysu w postaci zakłóceń w wynikach przewozowych utrzymywały się jeszcze w poszczególnych kwartałach 2023 r. Badania uzupełniające pokazały ponadto, że w transporcie kolejowym zakłócenia popytowe utrzymywały się jeszcze po wygaśnięciu najgłębszej fazy kryzysu. Mimo stopniowego zbliżania się wartości rzeczywistych do prognoz, nawet w 2022 r. rynek nie osiągnął w pełni poziomu możliwego do uzyskania w scenariuszu bez pandemii. W przypadku transportu publicznego w aglomeracji warszawskiej odnotowano natomiast nie tylko gwałtowny spadek liczby pasażerów, lecz także zmianę kierunku trendu pracy przewozowej oraz przekształcenia w strukturze sprzedaży biletów. Ogółem uzyskane wyniki pokazały, że wpływ pandemii nie ograniczał się wyłącznie do głębokich i trwałych zaburzeń popytowych, lecz zasadniczo odzwierciedlał także zróżnicowaną odporność poszczególnych gałęzi transportu.

Mając na względzie osiągnięte rezultaty można stwierdzić, że problem szczegółowy **PS2** został rozwiązany. Badania pokazały, że kryzysy zdrowotne wpływają na transport pasażerski przede wszystkim poprzez zaburzenia w mobilności społeczeństwa prowadzące do poważnego załamania poziomu przewozów, jak i zaburzeń dynamiki zmian popytu, przy czym skala zakłóceń, a następnie procesy odbudowy nie są jednakowe we wszystkich gałęziach transportu. Uzyskane wyniki stanowią podstawę do potwierdzenia hipotezy szczegółowej **HS2**.

Wykazano nie tylko sam spadek liczby pasażerów, ale również, że zaburzenia dynamiki zmian popytu miały charakter wyraźnie zróżnicowany pomiędzy gałęziami. Miało to odzwierciedlenie zarówno w początkowej głębokości załamania przewozów, jak i w odmiennym czasie utrzymywania się skutków kryzysu.

W odniesieniu do całości rozprawy przeprowadzone w tym zakresie badania stanowią ważny element podjętych rozważań naukowych, koncentrując się na kryzysach zdrowotnych i możliwościach zastosowania modelowania matematycznego do analizowania zakłóceń o nagłym charakterze. Wnoszą do rozprawy ilościową ocenę zmian zachodzących w konkretnych gałęziach pasażerskiego transportu w Polsce pod wpływem zagrożenia o podłożu epidemicznym biorąc jako przykład pandemię COVID-19. Co więcej, poza analizą i oceną skutków kryzysu zdrowotnego, wskazane zostały rekomendacje zorientowane na wzmacnianie odporności transportu pasażerskiego na podobne zjawiska w przyszłości.

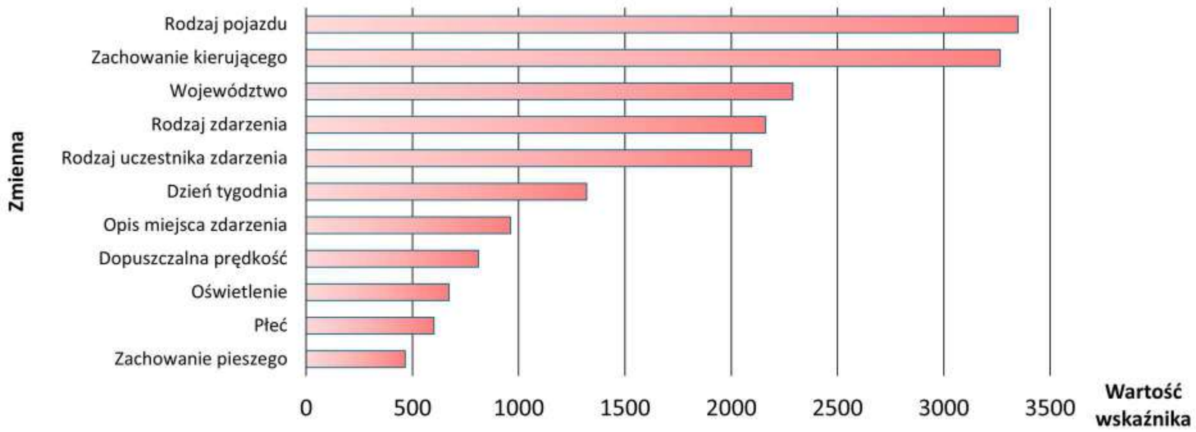
3.3. Procesy transportowe w sytuacjach kryzysu społecznego i militarnego [publikacja P5]

Artykuł **P5** dotyczy kompleksowej analizy funkcjonowania procesów transportowych w warunkach niepewności, obejmując zagadnienia związane z charakterystyką i typologią współczesnych kryzysów, ich oddziaływaniem na transport oraz możliwościami wykorzystania modelowania matematycznego w aspekcie badania takich zjawisk. Opracowanie podkreśla, że współczesne procesy transportowe funkcjonują w warunkach oddziaływania zróżnicowanych kryzysów, a każdy z nich może prowadzić do odmiennych konsekwencji. Jednym z typów zjawisk analizowanych w **P5** był kryzys społeczny powiązany z problemami bezpieczeństwa ruchu drogowego [85]. Do najbardziej dotkliwych konsekwencji funkcjonowania współczesnych systemów transportowych należą wypadki drogowe [86, 87]. Skutki tych zdarzeń wykraczają poza bezpośrednich uczestników, oddziałując także na rodziny poszkodowanych i świadków wypadków, wpływając tym samym na poczucie bezpieczeństwa w społeczeństwie. Zdarzenia drogowe generują ponadto znaczące koszty ekonomiczne, związane z leczeniem oraz rehabilitacją rannych, naprawą uszkodzonej infrastruktury i pojazdów czy utratą dochodów, wynikającą z niezdolności do pracy. W konsekwencji obciążony zostaje również system ochrony zdrowia, zwłaszcza w przypadku konieczności długotrwałego leczenia poszkodowanych [85]. Na szczególną uwagę zasługuje przy tym skala oraz trwałość tego zjawiska. W przeciwieństwie do nagłych zagrożeń, skutki wypadków drogowych ujawniają się w sposób rozproszony, jednak w długiej perspektywie obejmują bardzo dużą liczbę ofiar [85]. Z tego względu problem wypadków drogowych należy traktować jako jeden z przejawów współczesnych kryzysów społecznych związanych z funkcjonowaniem transportu.

Skala tego zjawiska ma charakter globalny. Według danych Światowej Organizacji Zdrowia wypadki drogowe przyczyniają się rocznie do około 1,19 mln zgonów na świecie, a ich ofiarami najczęściej są osoby młode, poniżej 30. roku życia, co dodatkowo podkreśla znaczenie tego problemu [88]. Bezpieczeństwo ruchu drogowego pozostaje istotnym wyzwaniem również w Unii Europejskiej. W 2024 r. na drogach UE zginęło około 20 tys. osób, co odpowiada średnio około 45 ofiarom na milion mieszkańców [89]. Dlatego w odpowiedzi na utrzymującą się skalę zjawiska rozwijana jest długofalowa polityka poprawy bezpieczeństwa ruchu drogowego oparta m.in. na koncepcji „Vision Zero", zakładającej dążenie do systematycznej redukcji liczby ofiar wypadków drogowych [86]. Na tle państw członkowskich poziom bezpieczeństwa pozostaje jednak zróżnicowany, a Polska wciąż należy do krajów o wyższej śmiertelności w wypadkach drogowych niż średnia unijna [87, 89]. W tym kontekście szczególnego znaczenia nabiera identyfikacja czynników wpływających na skalę oraz charakter zdarzeń komunikacyjnych, co stanowi istotny element kształtowania działań ukierunkowanych na zwiększenie odporności transportu na wyzwania w obszarze bezpieczeństwa ruchu drogowego.

Zagadnienie to rozwinięto między innymi w artykule **U9**, do którego bezpośrednio odwołuje się **P5**. Oceniony został wpływ wybranych zmiennych na bezpieczeństwo ruchu drogowego w Polsce, wyrażone poziomem obrażeń i liczbą ofiar w wypadkach, a także opracowano modele uczenia maszynowego, umożliwiające identyfikację zdarzeń drogowych oraz predykcję ich skutków dla uczestników.

Na wstępnym etapie analizy, przy użyciu algorytmu Random Forest oraz wskaźnika Mean Decrease Gini, spośród zestawu 24 zmiennych wyodrębniono 11 o najsilniejszym wpływie na poziom bezpieczeństwa ruchu drogowego. Ranking wyselekcjonowanych zmiennych przedstawiono na rysunku 3.3.1.



Rys. 3.3.1. Wartości wskaźnika Mean Decrease Gini dla wyodrębnionych zmiennych

Biorąc pod uwagę docelowo wybrane zmienne przeprowadzono pogłębioną analizę mającą na celu identyfikację zależności oraz wzorców charakteryzujących zdarzenia zachodzące na polskich drogach. Następnie opracowano modele oparte na algorytmach uczenia maszynowego, tj. K-Nearest Neighbors, Random Forest oraz Recursive Partitioning and Regression Trees, służące klasyfikacji ciężkości obrażeń u uczestników na podstawie zmiennych opisujących zdarzenia drogowe. Zbiór danych podzielono na część treningową (85%) i testową (15%). Oprócz tego przygotowano kontroler walidacji krzyżowej, w ramach którego dane treningowe podzielono na 10 podzbiorów. Opracowane modele klasyfikacyjne oceniono z wykorzystaniem metryk takich jak dokładność (*ang. accuracy),* współczynnik Kappa Cohena (*κ*) oraz czułość (*ang. sensitivity*) dla poszczególnych klas obrażeń. Uzyskane wyniki zestawiono w tabeli 3.3.1.

Tabela 3.3.1. Zestawienie wartości metryk oceny dla opracowanych modeli

Model	**Dokładność [%]**	**Kappa (κ)**	**Czułość [%]**			
			Brak obrażeń	**Lekkie obrażenia**	**Ciężkie obrażenia**	**Zgony**
KNN	64,20	0,42	88,90	62,72	14,83	6,23
RF	63,02	0,41	84,95	59,03	24,90	12,17
RPart	62,86	0,37	97,13	56,11	0	0

Najwyższą dokładność odnotowano dla modelu KNN, przy porównywalnych wartościach współczynnika Kappa względem modeli RF oraz RPart. Analiza czułości wskazuje, że wszystkie modele najlepiej identyfikowały klasę „brak obrażeń", natomiast znacznie gorzej rozpoznawały rzadziej występujące klasy, tj. „ciężkie obrażenia" oraz „zgony", co wynika z niezrównoważonego charakteru analizowanego zbioru danych. Na podstawie uzyskanych rezultatów można stwierdzić, że najlepszy wybór dla niezrównoważonych danych, szczególnie gdy celem jest identyfikacja rzadkich klas, stanowi model Random Forest. W sytuacjach, gdy kluczowa jest najwyższa dokładność ogólna, kompromis zapewnia model K-Nearest Neighbors. Z kolei model RPart może być traktowany jako podejście bazowe, wymagające jednak dalszych ulepszeń w celu poprawy zdolności rozpoznawania rzadkich klas.

W publikacji **P5** podkreślono, że modele uczenia maszynowego mogą wspierać kształtowanie odporności transportu na trwały i rozproszony kryzys społeczny, jakim są wypadki drogowe, zwłaszcza te, prowadzące do poważnych obrażeń uczestników ruchu. Zastosowane modele pozwoliły na identyfikację czynników zwiększających prawdopodobieństwo wystąpienia obrażeń oraz na wykrywanie powtarzalnych wzorców ryzyka związanych z określonymi typami zdarzeń i warunkami ich występowania. W praktyce wykorzystanie takich modeli może wspomóc podejmowanie decyzji dotyczących poprawy infrastruktury transportowej, hierarchizacji i planowania działań prewencyjnych oraz interwencji na poziomie lokalnym i krajowym, w tym również w zakresie zmian regulacyjnych (np. ustalania limitów prędkości). Z drugiej jednak strony badania uwydatniły, że skuteczność modeli ML w dużym stopniu zależy od jakości, kompletności i spójności danych. Dlatego istotną rekomendacją jest rozwój w Polsce zintegrowanego systemu gromadzenia i udostępniania informacji o zdarzeniach drogowych, natężeniu ruchu oraz warunkach środowiskowych [85]. Jest to warunek dla pełniejszego wykorzystania potencjału algorytmów uczenia maszynowego w ograniczaniu społecznych skutków wypadków drogowych, a tym samym wzmacnianiu odporności systemu transportowego na tego typu wyzwania.

Uzupełniającą rolę w kontekście kryzysu społecznego pełni publikacja **U10**, w której zbadano zależności pomiędzy liczbą wypadków drogowych w Polsce, a wybranymi czynnikami czasowymi związanymi z kalendarzem, tj. miesiącem oraz dniem tygodnia występowania zdarzeń. W opracowaniu zwrócono również uwagę na szerszy kontekst zmian zachodzących w funkcjonowaniu transportu drogowego w Polsce, związanych ze wzrostem mobilności społeczeństwa oraz dynamicznym rozwojem motoryzacji.

Podstawę badania stanowiły dane dotyczące wypadków drogowych w Polsce w latach 2014–2023. Ich analiza w całym rozpatrywanym okresie wskazała na ogólną tendencję spadkową liczby zdarzeń, czemu towarzyszył również spadek liczby osób rannych oraz ofiar śmiertelnych. Następnie przeanalizowano zróżnicowanie liczby wypadków w zależności od miesiąca oraz dnia tygodnia. Ze względu na brak zgodności badanych rozkładów z rozkładem normalnym, potwierdzony testem Lillieforsa, do badania istotności różnic pomiędzy poszczególnymi grupami zastosowano nieparametryczny test Kruskala–Wallisa. Uzyskane wyniki wskazały na występowanie istotnych statystycznie różnic w liczbie wypadków drogowych pomiędzy miesiącami oraz dniami tygodnia. Szczegółową interpretację tego zróżnicowania przeprowadzono na podstawie analizy rozkładów liczby wypadków w poszczególnych grupach czasowych. Zaobserwowano, że największa liczba zdarzeń występuje w miesiącach letnich, tj. od czerwca do października, co można wiązać ze zwiększoną mobilnością społeczeństwa w okresie wakacyjnym. Poza tym w listopadzie i grudniu odnotowano stosunkowo wysokie wartości mediany, co może pozostawać w związku ze zwiększoną liczbą podróży w okresach świątecznych. W przypadku dni tygodnia różnice są mniej wyraźne, jednak najwyższą liczbę wypadków obserwuje się w piątki, natomiast najniższą w niedziele. Prawidłowość tę można wiązać z większym natężeniem ruchu drogowego pod koniec tygodnia oraz niższą mobilnością w dni wolne od pracy.

Wyniki z publikacji **U10** potwierdzają, że czynniki czasowe związane z kalendarzem stanowią jeden z elementów różnicujących liczbę zdarzeń drogowych w Polsce. Zróżnicowanie liczby wypadków w zależności od miesiąca oraz dnia tygodnia wskazuje na istotne znaczenie uwarunkowań czasowych w obszarze bezpieczeństwa ruchu drogowego. Rozpoznanie tego typu zależności może wspomagać identyfikowanie okresów zwiększonego ryzyka oraz stanowić punkt odniesienia dla podejmowania środków prewencyjnych, ukierunkowanych na ograniczanie ich liczby. Przede wszystkim obserwacje te mogą sprzyjać lepszemu dostosowaniu działań związanych z organizacją ruchu, prowadzeniem czynności kontrolnych i kampanii informacyjnych na rzecz poprawy bezpieczeństwa.

Kolejnym typem zjawisk oddziałujących na funkcjonowanie transportu wskazanym w publikacji **P5** były kryzysy o podłożu militarnym. W artykule wskazano, że konflikty zbrojne mogą prowadzić do zniszczeń infrastruktury transportowej, ograniczeń w funkcjonowaniu przestrzeni powietrznej i morskiej czy zawieszania połączeń międzynarodowych [85]. W efekcie dochodzi do zakłócenia dotychczasowej organizacji przepływów osób i towarów, wzrostu obciążenia alternatywnych korytarzy transportowych oraz pogorszenia warunków wymiany gospodarczej. Ponadto kryzysy militarne często wywołują także masowe migracje ludności, wpływające na zmiany mobilności w regionach przyjmujących. Przykładem takiej sytuacji jest wojna na Ukrainie, która spowodowała znaczny napływ ludności do państw Europy Środkowo-Wschodniej, w tym do Polski, co wywołało zauważalne obciążenie systemów transportowych, zwłaszcza w dużych ośrodkach miejskich. Efekty tego zjawiska były widoczne m.in. w Warszawie, gdzie wzrost liczby uchodźców przełożył się na popyt na przewozy pasażerskie.

Rozważania te zostały rozwinięte w artykule **U7**, który został także wykorzystany w publikacji **P5** jako jeden z przykładów zastosowania modeli szeregów czasowych w badaniach nad transportem w warunkach kryzysu zdrowotnego i militarnego. W pracy dokonano analizy i oceny wpływu globalnych kryzysów mających miejsce w latach 2019–2022 na funkcjonowanie procesów transportowych w publicznym transporcie zbiorowym, na przykładzie aglomeracji warszawskiej.

Skoncentrowano się na trzech okresach – przedpandemicznym, od wybuchu pandemii COVID-19 oraz na rozpoczynającym się od eskalacji konfliktu rosyjsko-ukraińskiego (luty 2022 r.). Analogicznie jak dla pandemii zastosowano wygładzanie wykładnicze szeregów czasowych metodą Browna i Holta, a następnie wyznaczono trendy liniowe, co pozwoliło uzyskać wyniki pokazane w tabelach 3.3.2–3.3.3.

Tabela 3.3.2. Parametry modeli wygładzania i trendów dla całkowitej liczby sprzedanych biletów

Okres	**Modele wygładzania wykładniczego**			**Model trendu liniowego**	
	α	**RMSE**	**MAPE [%]**	**Równanie**	***R*²**
Przedpandemiczny	0,19	578559	6,84	$y = 29858x + 6 \times 10^6$	0,63
Od wybuchu pandemii	0,75	1141982	22,08	$y = 196492x + 3 \times 10^6$	0,75
Od rozpoczęcia wojny	0,82	713805	5,93	$y = 315724x + 7 \times 10^6$	0,80

Tabela 3.3.3. Parametry modeli wygładzania i trendów dla wykonanej pracy przewozowej

Okres	**Modele wygładzania wykładniczego**				**Model trendu liniowego**	
	α	***β***	**RMSE**	**MAPE [%]**	**Równanie**	***R*²**
Przedpandemiczny	0,41	0,30	1159023	5,90	$y = 113854x + 1 \times 10^7$	0,69
Od wybuchu pandemii	0,01	-	735103	3,71	$y = -15142x + 2 \times 10^7$	0,73
Od rozpoczęcia wojny	0,27	-	989543	4,79	$y = 100105x + 2 \times 10^7$	0,61

Popyt na usługi transportu publicznego analizowano pod względem liczby sprzedanych biletów w komunikacji miejskiej. Na skutek wybuchu pandemii wartość ta spadła w 2020 r. do poziomu 4,88 mln względem 7,08 mln z 2019 r. W kolejnych latach obserwowana była jednak zwiększona sprzedaż osiągająca w 2022 r. aż 8,47 mln. Oznacza to, że po okresie spadków wywołanych pandemią ponownie obserwowano wzrost korzystania z transportu publicznego. Jak pokazują wyniki zestawione w tabelach 3.3.2 i 3.3.3. w zależności od konkretnego okresu w latach 2019–2022 zauważalne było zróżnicowanie kierunków i tempa zmian wskaźników realizacji procesów transportowych. Najbardziej dynamiczne zmiany zaobserwowano w okresie po wybuchu wojny rosyjsko-ukraińskiej. Tempo wzrostu liczby sprzedanych biletów osiągnęło wówczas poziom około 315,72 tys. miesięcznie, co stanowiło najwyższą wartość spośród wszystkich analizowanych okresów. W odniesieniu do pracy przewozowej wykonanej przez środki transportu publicznego w aglomeracji warszawskiej widoczna była natomiast zmiana kierunku trendu. W okresie od wybuchu pandemii trend był malejący, a tempo spadku wynosiło około 15,14 tys. wozokilometrów miesięcznie. Z kolei po rozpoczęciu wojny rosyjsko-ukraińskiej obserwowano tendencję wzrostową, a tempo zmian kształtowało się na poziomie około 100,1 tys. wozokilometrów miesięcznie. Podobne zależności obserwowano także w przypadku liczby przewiezionych pasażerów. Po gwałtownym spadku od momentu wybuchu pandemii, którego tempo wynosiło około 102,96 mln osób rocznie, od lutego 2022 r. obserwowano trend wzrostowy, a tempo zmian liczby przewiezionych pasażerów osiągnęło poziom około 44,46 mln osób rocznie. Wszystkie te prawidłowości można wiązać z rosnącym popytem na przewozy w aglomeracji warszawskiej, kształtowanym przez kilka współwystępujących czynników, w tym m.in. stopniowe znoszenie restrykcji pandemicznych oraz napływ ludności migrującej z Ukrainy.

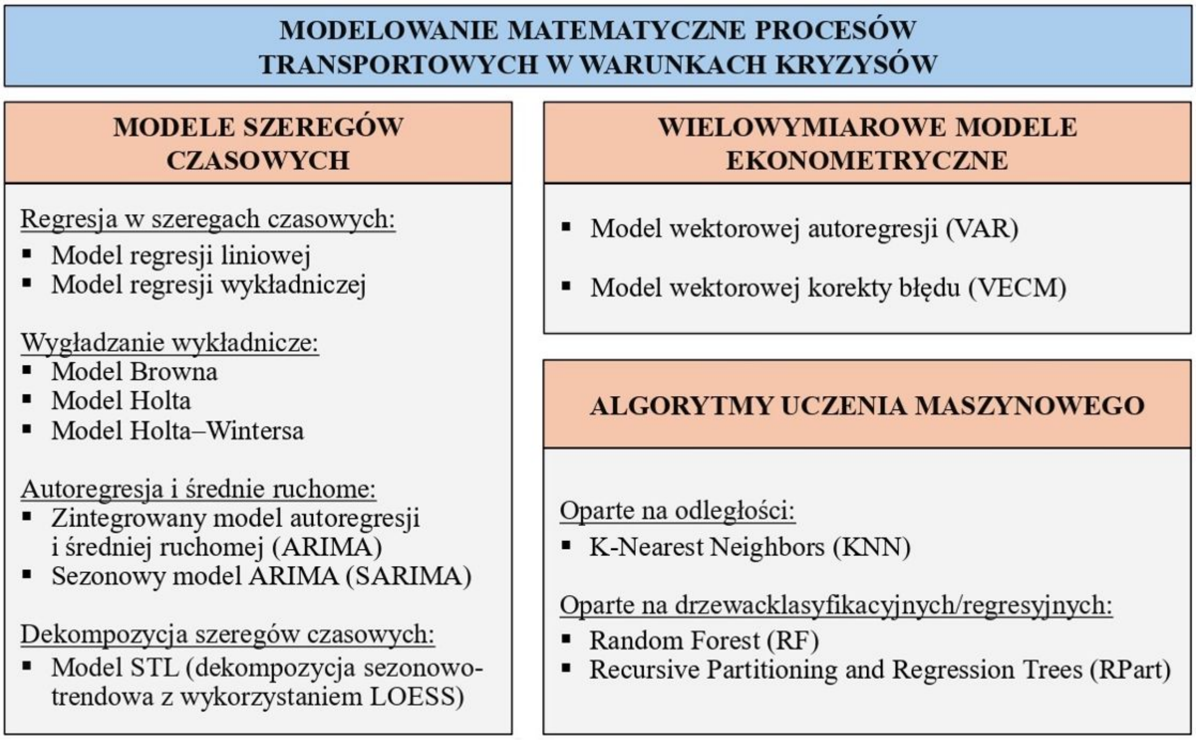
Wyniki z artykułu **U7** zostały wykorzystane w publikacji **P5**, aby podkreślić znaczenie podejścia obejmującego wygładzanie wykładnicze metodami Browna i Holta oraz analizę trendu liniowego w badaniach nad funkcjonowaniem transportu w przypadku nagłych i trudnych do przewidzenia zakłóceń jak wybuch pandemii COVID-19 czy też napływ uchodźców do dużych ośrodków miejskich. Modelowanie matematyczne umożliwiło określenie kierunku oraz tempa zmian analizowanych wskaźników w poszczególnych okresach, co pozwoliło na identyfikację momentów przełomowych w funkcjonowaniu zbiorowego transportu publicznego w warunkach związanych zarówno z pandemią jak i konfliktem zbrojnym [85].

Uzyskane wyniki wskazują, że współczesne kryzysy o zróżnicowanym podłożu mogą w odmienny sposób oddziaływać na procesy transportowe w ośrodkach miejskich. O ile pandemia COVID-19 doprowadziła do znaczącego ograniczenia mobilności i spadku wykorzystania transportu publicznego, o tyle wojna na Ukrainie, zwłaszcza w początkowej fazie, spowodowała napływ ludności, który przyczynił się do zwiększenia popytu na przewozy pasażerskie w Warszawie. Badanie pokazuje zatem, że konsekwencje kryzysu militarnego w postaci gwałtownej migracji do państwa sąsiedniego nie były tak bezpośrednie ani tak dotkliwe dla funkcjonowania komunikacji miejskiej, jak skutki globalnego kryzysu zdrowotnego wywołanego pandemią COVID-19. Jednocześnie konflikt rosyjsko-ukraiński uwidocznił potrzebę przygotowania systemów transportu publicznego dużych aglomeracji na nagłe wzrosty liczby użytkowników. W świetle tych ustaleń można wskazać kilka praktycznych kierunków działań:

- Należy stosować bieżącą analizę liczby i struktury sprzedawanych biletów w celu identyfikacji zmian potrzeb przewozowych pojawiających się w sytuacji kryzysu militarnego skutkującego napływem ludności do ośrodków miejskich. Zmiany w udziale poszczególnych rodzajów biletów mogą odzwierciedlać nie tylko wzrost liczby użytkowników transportu publicznego, lecz także przekształcenia w sposobach korzystania z transportu – od podróży incydentalnych do regularnych dojazdów związanych z pracą, edukacją lub dłuższym pobytem w mieście. Wykorzystanie tego wskaźnika w zarządzaniu transportem miejskim powinno stanowić podstawę korygowania istniejącej oferty przewozowej, w tym częstotliwości kursowania, przebiegu tras oraz obsługi relacji o rosnącym znaczeniu przewozowym. W rezultacie umożliwi to nie tylko szybsze rozpoznawanie zmian popytu, ale również pozwoli na dostosowanie systemu transportu miejskiego do kolejnych etapów zjawiska migracyjnego.

- Wskazane jest prowadzenie porównań zmian liczby sprzedawanych biletów i liczby przewożonych pasażerów ze zmianami poziomu wykonanej pracy przewozowej (np. w ujęciu miesięcznym). Utrzymywanie się rozbieżności pomiędzy tymi wskaźnikami powinno być postrzegane jako sygnał, że zmiany potrzeb przewozowych zachodzą szybciej niż reakcja systemu transportowego. Identyfikacja okresów, w których podaż przewozów przestaje odpowiadać rzeczywistemu popytowi, pozwoli nie tylko na wcześniejsze rozpoznanie niedostosowania systemu transportu miejskiego do zmian wywołanych kryzysem militarnym, ale także na wykorzystanie tej rozbieżności na potrzeby oceny podatności systemu transportowego na skutki kryzysu związanego z nagłym napływem ludności.

Kolejnym równie istotnym elementem publikacji **P5** był przegląd możliwości wykorzystania modelowania matematycznego do analizy i oceny funkcjonowania procesów transportowych w warunkach kryzysów. Przeprowadzona analiza podejść modelowych, mających zastosowanie w obszarze transportu, wskazała na ich istotne zróżnicowanie, wynikające z odmiennych konstrukcji i założeń modeli, sposobu opisu badanych zjawisk oraz związanych z tym możliwości. Z tego względu, dla modeli rozpatrywanych w ramach prowadzonych badań, zaproponowano ich systematyzację według podejścia analitycznego, którą przedstawiono na rysunku 3.3.2.



Rys. 3.3.2. Systematyzacja modeli rozpatrywanych w toku badań

Powyższe uporządkowanie pozwala wnioskować, że nie istnieje jedno uniwersalne podejście możliwe do zastosowania we wszystkich przypadkach. Rozszerzeniem zaproponowanej systematyzacji modeli matematycznych, wywodzącej się z przeglądu i podziału ujętego w publikacji **P5**, było syntetyczne zestawienie zastosowań modeli matematycznych, które zostały wykorzystane w toku całych badań, co zostało zaprezentowane w tabeli 3.3.4.

Tabela 3.3.4. Zestawienie zastosowań modeli wykorzystanych w toku całych badań

Typ kryzysu	Model	Zastosowanie
Kryzys środowiskowy	Model VECM (z analizą IRF)	Ocena współzależności między zmiennymi ekonomicznymi i środowiskowymi związanymi z transportem; analiza reakcji systemu na zakłócenia; wsparcie decyzji w zakresie polityki energetycznej i fiskalnej.
Kryzys gospodarczy		
Kryzys środowiskowy	Model ARIMA/ regresji wykładniczej	Ocena tempa wzrostu mocy zainstalowanej w OZE; określenie możliwego momentu osiągnięcia docelowego poziomu w kontekście transformacji energetycznej.
Kryzys gospodarczy		
Kryzys zdrowotny	Model Holta–Wintersa	Ocena kondycji rynków pasażerskich przewozów powietrznych; oszacowanie skali strat i stopnia osiągnięcia referencyjnego poziomu przewozów; identyfikacja wzorców odporności.
	Model SARIMA lub Holta–Wintersa	Ocena wpływu na poziom przewozów pasażerskich; prognozowanie liczby pasażerów w warunkach zakłóceń; wsparcie planowania działalności transportowej.
	Model STL	Ocena zmian w komponentach trendu i sezonowości w związku z kryzysem zdrowotnym; wsparcie planowania działalności transportowej.
	Model SARIMA	Ocena skali załamania popytu; wskazanie momentu osiągnięcia przez rynek poziomu możliwego w przypadku braku kryzysu.
Kryzys zdrowotny	Model Holta/Browna (z analizą trendu liniowego)	Określenie kierunku i tempa zmian wskaźników realizacji procesów transportowych z ograniczeniem wpływu krótkookresowych wahań; identyfikacja momentów przełomowych w funkcjonowaniu transportu publicznego; oszacowanie skali oddziaływania kryzysów.
Kryzys militarny		
Kryzys społeczny	KNN/RF/RPart	Wskazanie czynników zwiększających prawdopodobieństwo wystąpienia obrażeń i zgonów; wykrywanie powtarzalnych wzorców ryzyka; predykcja skutków zdarzeń drogowych; wsparcie podejmowania decyzji w zakresie działań prewencyjnych oraz poprawy bezpieczeństwa ruchu drogowego.

Całościowe ujęcie modeli matematycznych wykorzystanych w badaniach, wraz z uwzględnieniem ich zastosowań na potrzeby analizy i oceny funkcjonowania procesów transportowych w warunkach współczesnych kryzysów potwierdza ich kluczową rolę w identyfikacji zachodzących zależności i oddziaływań, ocenie odporności na występujące zagrożenia, a w efekcie także w formułowaniu rekomendacji dla sektora transportu.

Reasumując, publikacja **P5** łączy wyniki dotyczące zarówno kryzysów społecznych, związanych z wciąż utrzymującą się skalą i ciężkością wypadków w ruchu drogowym, jak i kryzysów militarnych – w tym przypadku dotyczących migracji ludności po wybuchu wojny na Ukrainie. Rozpoczęto od identyfikacji wzorców ryzyka i czynników kształtujących bezpieczeństwo ruchu drogowego w Polsce. Dalej skupiono się na analizie i ocenie zmian wskaźników realizacji procesów transportowych w publicznym transporcie zbiorowym w aglomeracji warszawskiej w związku z napływem uchodźców. Zaprezentowane w podrozdziale 3.3 badania nie tylko dostarczyły kolejnych przykładów wyzwań, z którymi musi zmagać się sektor transportu, lecz umożliwiły również uporządkowanie całości przeprowadzonych analiz.

Najważniejsze, uzyskane wyniki wskazują, że bezpieczeństwo ruchu drogowego w Polsce pozostaje obszarem, w którym występują rozpoznawalne i powtarzalne prawidłowości dotyczące liczby zdarzeń, jak i ciężkości ich skutków. Wykazano istotne statystycznie różnice w liczbie wypadków pomiędzy miesiącami oraz dniami tygodnia, co pozwoliło zidentyfikować okresy zwiększonego ryzyka. Co więcej, modelowanie z wykorzystaniem algorytmów ML potwierdziło, że ciężkość wypadków jest determinowana przez określony zestaw czynników opisujących zdarzenia drogowe, przy czym proponowane modele różniły się pod względem dokładności i czułości klasyfikacji obrażeń. Z kolei w przypadku kryzysu militarnego wykazano, że w transporcie publicznym w aglomeracji warszawskiej doszło do zmiany kierunku oraz tempa zmian analizowanych wskaźników, co odzwierciedlało wzrost popytu na przewozy na skutek napływu ludności migrującej. Ponadto zwrócono uwagę na istotne zróżnicowanie podejść modelowych mających zastosowanie w badaniach dotyczących funkcjonowania procesów transportowych w warunkach różnych kryzysów. Dokonano podziału modeli matematycznych zwracając uwagę na ich zróżnicowanie pod względem konstrukcji i założeń oraz sposobu opisu zjawisk. Pozwoliło to na systematyzację modeli rozpatrywanych w toku rozprawy, co następnie rozszerzono o syntetyczne zestawienie ich zastosowań. W rezultacie pokazano, że w analizie i ocenie procesów transportowych konkretne modele matematyczne nie znajdują zastosowania w każdym z przypadków, natomiast w zależności od specyfiki analizowanego problemu mogą się wzajemnie uzupełniać, prowadząc do uzyskania pełniejszego obrazu rozpatrywanego zjawiska.

Podrozdział 3.3 przedstawia badania stanowiące odpowiedź na problem szczegółowy **PS3**, gdyż stwierdzono, że istnieją zmiany w przebiegu wskaźników opisujących realizację procesów transportowych w aglomeracji warszawskiej w odniesieniu do liczby przewiezionych pasażerów oraz wykonanej pracy przewozowej. Zidentyfikowane zostały także wzorce dotyczące skutków zdarzeń drogowych. Uzyskane rezultaty dały podstawę do potwierdzenia hipotezy szczegółowej **HS3**. Badania wykazały, że kryzys militarny dotyczący napływu ludności migrującej po wybuchu wojny na Ukrainie doprowadził do zmiany kierunku trendu i wzrostu tempa zmian liczby pasażerów oraz wykonanej pracy przewozowej w warszawskim transporcie publicznym. Jednocześnie kryzys społeczny, związany z wypadkami drogowymi w Polsce ujawnił występowanie powtarzalnych wzorców ryzyka w zakresie ciężkości obrażeń wśród uczestników, determinowanych czynnikami opisującymi zdarzenia.

Na tle całej rozprawy niniejszy podrozdział pełni podwójną rolę. Z jednej strony rozszerza badania o kolejne typy kryzysów oddziałujących na transport. Z drugiej zaś integruje warstwę analityczną i metodyczną cyklu powiązanych tematycznie publikacji, stanowiąc tym samym kompleksowe ujęcie ogółu przeprowadzonych rozważań. Odzwierciedleniem tego jest wkład w pracę w postaci analizy zmian w publicznym transporcie zbiorowym pod wpływem kryzysu militarnego, identyfikacji wzorców ryzyka i czynników kształtujących bezpieczeństwo ruchu drogowego, a także systematyzacji modeli matematycznych oraz syntetycznego zestawienia ich zastosowań. W ten sposób przeprowadzone badania wzmacniają odpowiedź na główny problem badawczy pokazując jak współczesne kryzysy wpływają na transport oraz w jaki sposób modelowanie może wspierać analizę tych zjawisk. Tym samym przyczyniają się do osiągnięcia celu pracy i pozytywnej weryfikacji hipotezy głównej potwierdzając, że odpowiednio dobrane modele matematyczne umożliwiają badanie oddziaływania współczesnych kryzysów na procesy transportowe, a przez to formułowanie rekomendacji na rzecz wzmacniania odporności transportu.

Niniejszy podrozdział zamyka zasadniczą część badań podejmowanych w rozprawie.

4. PODSUMOWANIE, WNIOSKI, KIERUNKI DALSZYCH BADAŃ

W niniejszej rozprawie skupiono się na dokonaniu analizy i oceny funkcjonowania procesów transportowych w warunkach współczesnych kryzysów o podłożu środowiskowym, gospodarczym, zdrowotnym, społecznym i militarnym. Każdemu z wymienionych typów kryzysów poświęcono szczegółową uwagę, badając ich wpływ na przebieg i organizację procesów transportowych, co znajduje odzwierciedlenie w przedstawionym do oceny cyklu publikacji. Celem badania była również identyfikacja sposobu kształtowania się procesów transportowych w warunkach poszczególnych zagrożeń, z zastosowaniem modeli matematycznych odpowiednio dobranych do charakteru danych empirycznych.

W pierwszym etapie rozważań naukowych szczególną uwagę poświęcono identyfikacji oraz usystematyzowaniu współczesnych kryzysów wpływających na sektor transportu. Opracowano typologię tych zjawisk, która stanowiła podstawę dalszych badań oraz modelowania procesów transportowych. Następnie przeprowadzono ocenę relacji występujących pomiędzy zużyciem energii końcowej w transporcie, emisjami CO_2 z transportu oraz dochodami budżetu państwa. W tym celu wykorzystano metodę kointegracji Johansena, model VECM oraz funkcję IRF, które pozwoliły na rozpoznanie zależności pomiędzy analizowanymi zmiennymi oraz ocenę znaczenia współczesnych wyzwań środowiskowych oraz gospodarczych dla funkcjonowania i rozwoju transportu w Polsce.

Druga część pracy obejmowała analizę wpływu kryzysów zdrowotnych na funkcjonowanie procesów transportowych. Przeprowadzono badania dotyczące pasażerskiego transportu w Polsce na przykładzie pandemii COVID-19. Zastosowano modele szeregów czasowych, w tym m.in. Holta–Wintersa i SARIMA, które umożliwiły ocenę strat w przewozach i analizę dynamiki zmian popytu. Na tym etapie skoncentrowano się również na zróżnicowaniu skali fluktuacji i przebiegu zakłóceń w poszczególnych gałęziach transportu.

Ostatnia, trzecia zasadnicza część badań dotyczyła procesów transportowych w warunkach kryzysów społecznych i militarnych. W pierwszej kolejności rozpatrzono kryzysy społeczne związane z bezpieczeństwem ruchu drogowego. Wykorzystano przede wszystkim algorytmy uczenia maszynowego, takie jak KNN, RF i RPart, aby określić czynniki, które wpływają na ciężkość wypadków oraz zidentyfikować wzorce ryzyka związane z okolicznościami występowania zdarzeń. Następnie zbadano wpływ kryzysu militarnego wywołanego wojną na Ukrainie i wzmożoną migracją ludności na funkcjonowanie publicznego transportu zbiorowego w aglomeracji warszawskiej. Analizie poddano zmiany liczby pasażerów, sprzedaży biletów oraz wykonanej pracy przewozowej, odnosząc je do zmian mobilności wywołanych wymuszoną migracją. Pozwoliło to określić sposób, w jaki miejski system transportowy reaguje na nagłe zakłócenia o charakterze militarnym.

Przeprowadzone badania wyróżniają się kompleksowym podejściem do problematyki odporności procesów transportowych na współczesne kryzysy. Dzięki zastosowaniu odpowiednich metod badawczych i doborowi właściwych modeli matematycznych, służących identyfikacji zmian zachodzących w procesach transportowych, nie tylko zidentyfikowano zachodzące zależności oraz przeanalizowano występujące w ostatnich latach zakłócenia, lecz również dokonano oceny odporności transportu na kryzysy, co pozwoliło na wyprowadzenie wniosków istotnych z perspektywy funkcjonowania transportu w warunkach niepewności. Istotny jest przy tym aplikacyjny wymiar przeprowadzonych badań. Na podstawie otrzymanych wyników opracowano rekomendacje oraz wskazano kierunki działań służących wzmacnianiu odporności sektora transportu. Dotyczyły one przede wszystkim ograniczania energochłonności i emisyjności transportu, rozwijania zdolności organizacyjnych transportu publicznego w sytuacjach nagłych zmian popytu, doskonalenia systemów monitorowania i prognozowania zakłóceń w przewozach oraz uwzględniania wzorców ryzyka w działaniach na rzecz poprawy bezpieczeństwa ruchu drogowego. Przeprowadzone analizy pozwoliły na weryfikację przyjętych założeń badawczych oraz rozwiązanie sformułowanego problemu rozprawy.

Najważniejsze wnioski wynikające z przeprowadzonych badań zostały uporządkowane i przedstawione w podziale na ogólne, szczegółowe, metodyczne i utylitarne.

Wnioski ogólne:

1. Oddziaływanie kryzysów na transport ma charakter zróżnicowany i zależy zarówno od rodzaju zakłócenia, jak i od specyfiki analizowanego procesu transportowego.
2. Transport w Polsce pozostaje pod wpływem trwałych zależności środowiskowo-gospodarczych, a nagłe kryzysy zdrowotne i militarne oraz czynniki kształtujące bezpieczeństwo ruchu drogowego prowadzą do zaburzeń jego funkcjonowania.
3. Zastosowanie metod i modeli matematycznych pozwala na identyfikację zmian, zależności i wzorców ryzyka w procesach transportowych, analizę skutków zakłóceń oraz ocenę odporności sektora, co wspiera formułowanie rekomendacji.

Wnioski szczegółowe:

1. Funkcjonowanie sektora transportu w Polsce pozostaje długookresowo determinowane jednocześnie przez czynniki środowiskowe i gospodarcze, co potwierdziło

zidentyfikowanie dwóch relacji kointegracyjnych pomiędzy zużyciem energii końcowej w transporcie, emisjami CO_2 z transportu oraz dochodami budżetu państwa.

2. Całkowite zużycie energii końcowej w transporcie pełni istotną rolę w kształtowaniu presji emisyjnej sektora i pozostaje powiązane z budżetowym wymiarem jego funkcjonowania, przy czym analiza IRF wykazała, że zależności te ujawniają się w sposób rozłożony w czasie.
3. Kryzysy zdrowotne o podłożu epidemicznym prowadzą do silnych zakłóceń w pasażerskim transporcie, jednak skala załamania, dynamika zmian popytowych oraz procesy odbudowy są zróżnicowane pomiędzy gałęziami, co potwierdza ich odmienną podatność na restrykcje mobilności i zmiany zachowań przewozowych w społeczeństwie.
4. Pandemia COVID-19 doprowadziła nie tylko do gwałtownego spadku liczby przewożonych pasażerów, lecz także do utrzymujących się przekształceń dynamiki popytu, gdyż nawet po wygaśnięciu najgłębszej fazy kryzysu nie odnotowano pełnego powrotu do poziomu przewozów możliwego do osiągnięcia w scenariuszu braku tego zagrożenia. Zjawisko to było szczególnie widoczne w transporcie powietrznym i kolejowym.
5. Najwyższą wrażliwość na skutki kryzysu zdrowotnego, spośród analizowanych gałęzi transportu pasażerskiego, wykazał transport powietrzny. Zarówno w Polsce, jak i na porównywanych rynkach europejskich, przejawiało się to poważną skalą spadku liczby pasażerów oraz rozciągającym się w czasie powrotem do poziomów referencyjnych.
6. Kryzys militarny wywołany wojną na Ukrainie i związana z nim przymusowa migracja ludności doprowadziły do nagłej zmiany przebiegu procesów transportowych w publicznym transporcie zbiorowym w aglomeracji warszawskiej, czego wyrazem była zmiana kierunku trendu oraz tempa zmian liczby pasażerów i wykonanej pracy przewozowej.
7. Kryzys społeczny związany z wypadkami drogowymi w Polsce ujawnił występowanie powtarzalnych wzorców ryzyka w zakresie ciężkości obrażeń uczestników. Skutki wypadków nie mają charakteru losowego, lecz są determinowane czynnikami opisującymi okoliczności zdarzeń.

Wnioski metodyczne:

1. Prowadzenie badań nad procesami transportowymi w warunkach kryzysowych wymaga zastosowania metod badawczych oraz modeli analitycznych właściwie dostosowanych

do charakteru analizowanego kryzysu, specyfiki procesu transportowego, właściwości danych empirycznych i horyzontu czasowego przyjętej analizy.

2. Nie istnieje uniwersalne podejście badawcze właściwe dla wszystkich analizowanych przypadków, dlatego zasadne jest łączenie komplementarnych technik i narzędzi analitycznych, w tym odpowiednio dobranych modeli matematycznych.
3. Metoda kointegracji Johansena, model VECM i IRF są użyteczne w badaniu zależności i reakcji na zakłócenia w otoczeniu środowiskowo-gospodarczym w transporcie.
4. Modele szeregów czasowych umożliwiają ocenę skali strat w przewozach, analizę dynamiki zmian popytu oraz rozpoznanie przebiegu i zróżnicowania zakłóceń w poszczególnych gałęziach transportu w warunkach nagłych kryzysów.
5. Algorytmy ML są w stanie identyfikować powtarzalne wzorce ryzyka i czynniki wpływające na poziom bezpieczeństwa w ruchu drogowym.

Wnioski utylitarne:

1. Wyniki przeprowadzonych badań mogą stanowić podstawę działań ukierunkowanych na ograniczanie emisyjności i energochłonności transportu, z uwzględnieniem zależności między zużyciem energii końcowej, emisjami i uwarunkowaniami budżetowymi.
2. Rozpoznane uwarunkowania środowiskowo-gospodarcze funkcjonowania sektora transportu mogą wspierać kształtowanie polityki fiskalnej i inwestycyjnej w transporcie, w tym ukierunkowanie środków publicznych na rozwój infrastruktury i technologii ograniczających emisyjność sektora transportu.
3. Ustalenia dotyczące kryzysów zdrowotnych i militarnych oraz ich wpływu na funkcjonowanie transportu pasażerskiego mogą być uwzględnione przez odpowiednich decydentów w procesie opracowywania scenariuszy organizacji przewozów w warunkach nagłych zakłóceń popytu.
4. Wyniki badań odnoszące się do kryzysów militarnych mogą służyć planowaniu rezerw przewozowych, zwiększających zdolność miejskich systemów transportowych do reagowania na nagłe wzrosty potrzeb przewozowych.
5. Zidentyfikowane wzorce ryzyka oraz czynniki wpływające na zdarzenia w ruchu drogowym mogą znaleźć zastosowanie w planowaniu działań prewencyjnych przez administrację publiczną, zarządców infrastruktury oraz służby odpowiedzialne za bezpieczeństwo ruchu drogowego.

Na podstawie przeprowadzonych badań można wskazać następujące kierunki dalszych prac badawczych:

1. Rozszerzenie zakresu przestrzennego badań na inne regiony lub kraje w celu porównania oddziaływania kryzysów oraz weryfikacji uzyskanych zależności w innych uwarunkowaniach.
2. Zweryfikowanie zaproponowanych modeli i bazujących na nich rekomendacji w praktyce funkcjonowania systemów transportowych, w szczególności w procesach planowania i zarządzania.
3. Integrowanie modeli matematycznych z rozwiązaniami wykorzystującymi dane strumieniowe, duże zbiory danych oraz sztuczną inteligencję, aby zwiększyć zdolności predykcyjne modeli, poszerzyć możliwości analizowania i monitorowania zakłóceń, zwłaszcza w czasie rzeczywistym.
4. Rozwijanie podejść bazujących na scenariuszach, które mogłyby wspierać podejmowanie decyzji w transporcie pod względem oceny konsekwencji różnych wariantów działań i przygotowania transportu na nowe kryzysy, w tym o charakterze wieloaspektowym.

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[c] Status pracy to przyjęta do publikacji – potwierdzone zaświadczeniem o akceptacji.

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mój udział polegał na przeprowadzeniu analizy formalnej, współudziale w przygotowaniu pierwotnej wersji tekstu, współudziale w redakcji i merytorycznym opracowaniu kolejnych wersji manuskryptu, sprawowaniu nadzoru nad przebiegiem prac oraz akceptacji ostatecznej wersji publikacji.

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Review

Recent Advances for the Development of Sustainable Transport and Their Importance in Case of Global Crises: A Literature Review

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Abstract: The 21st century is a time of rapid development, marked by technological advances, globalization, and international cooperation. It is also a period that has witnessed numerous global crises. In light of recent events, such as the migration crisis, the COVID-19 pandemic, and the escalation of the conflict between Ukraine and Russia, it is crucial to consider how to ensure economic stability and enhance the security of the transportation sector in the face of emerging threats. The goal of this publication is to identify the latest solutions in sustainable transportation development and to highlight their relevance in the context of potential global crises. To achieve this, a systematic review of the current research on transportation industry innovations was conducted using 4 different databases, yielding 492 results. From these, 223 publications were selected for analysis based on established criteria. The selected transport solutions were grouped into specific categories, and then their relevance in the context of global crises was discussed. The findings highlighted key solutions essential for economic stability and transport sector safety in potential crisis situations, while also pointing to further research directions. Additionally, they offer actionable concepts for transport organizers to promote a more resilient and sustainable flow of passengers and goods in anticipation of future crises.

Keywords: sustainable transport; transport development; modern solutions; global crises; military conflicts; COVID-19 pandemic; climate crisis; migration; literature review

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1. Introduction

The modern world remains exposed to a variety of threats, which, as the past decades have shown, can lead to serious global crises. The 21st century is undoubtedly an era of profound transformation and rapid development, with technological advances, economic globalization, and international cooperation at the forefront [1,2]. However, it is also a time marked by numerous global crises with diverse origins [3–5]. For instance, in 2008, the global financial and banking crisis stemmed from the collapse of the mortgage market in the USA [6]. In 2015, Europe faced significant challenges due to the sudden influx of migrants and refugees [7]. In March 2020, the World Health Organization (WHO) declared the COVID-19 pandemic, which disrupted all aspects of life and shook the global economy [8]. The 21st century has also been marked by ongoing military crises, as evidenced by the armed conflict between Ukraine and Russia [9], as well as continued geopolitical tensions in the Middle East [10]. These challenges are further intensified by ongoing environmental degradation and climate system disruptions, which negatively impact human health, the economy, and society [11,12].

Given the recent crises, it is essential to explore how to ensure the stability and security of the global economy in the face of new potential threats. One of the most important sectors significantly affecting the daily lives of billions of people worldwide is transport [13]. However, it is also responsible for a substantial portion of greenhouse gas emissions, which exacerbate the climate crisis. Therefore, developing sustainable transport, which balances efficiency, low emissions, and minimal environmental impact, has become a key challenge for the modern world. Recent years have seen rapid development of technology and innovative solutions aimed at transforming the transport sector into one that is not only more environmentally friendly but also more resilient to disruptions, such as a future pandemic or another global crisis [14]. Electromobility, infrastructure development, intelligent transport systems (ITS), and innovative approaches to logistics and public transport are just some of the directions in which modern transport is evolving. However, the implementation of these solutions depends on various factors, such as government policies, technology availability, and international cooperation. Equally important is to ensure that these innovations can be effectively applied and have practical uses during crises [15].

The purpose of this publication is to identify the latest solutions in sustainable transport development and to highlight their relevance in the context of potential global crises. This study is based on two key research questions:

- What solutions related to sustainable transport development are described in the latest scientific research?
- What is the significance of recent advances in transport solutions in the context of potential global crises?

This article presents a systematic review of current research on transport industry innovations, categorizing these solutions and discussing their importance in the context of possible global crises. The findings not only highlight key solutions for ensuring the stability of the economy and the transport sector during crises but also suggest future research directions focused on developing strategies to improve security in the face of potential threats. Furthermore, these findings provide transport organizers with proposals for practical solutions that could help achieve a more resilient and sustainable flow of passengers and goods in the event of future crises.

The article is structured into several sections. Following the introduction, Section 2 presents the theoretical framework, which outlines the categorization of modern transport solutions and the classification of contemporary global crises. This section also defines the concept of 'sustainable transport' and explains its principles. Section 3 describes the systematic literature review methodology used in the study. Section 4 presents the results of the analysis of the selected body of literature. Finally, Section 5 concludes with a summary of the practical and theoretical contributions of the study, along with a discussion of its limitations and potential directions for further research.

2. Theoretical Framework: Definitions and Classifications

2.1. Classification of Modern Solutions in Transport

Conducting a review of research on the latest advances in the area of sustainable transport development in the context of their importance for potential crises requires first and foremost considering the theoretical frameworks related to modern transport solutions. These solutions can be defined as a set of methods, tools, technologies, or strategies for moving people or goods from one place to another. They may encompass various aspects of transport operations, such as infrastructure, management systems, technology, and the organization of logistics processes [16,17].

The literature provides numerous examples of solutions that have been successfully implemented in transport and widely embraced by society [18–20]. However, in an era of rapid technological advancement—where artificial intelligence (AI), advanced automation systems, the Internet of Things (IoT), and Big Data technologies [21,22] are increasingly influential—the emergence of new innovations is inevitable. Modern innovations, such as autonomous vehicles, unmanned aerial vehicles (UAVs) [23], and intelligent traffic management systems, are continually transforming the transport sector, making it more efficient, safer, and greener [24–26]. Research in the area of transport system models (TSMs) is also worth noting, as they not only can reduce risk but also increase evacuation preparedness in the event of disastrous events [27]. The classification of these modern transport solutions is not strictly defined and continues to evolve as new technologies emerge and research advances. Given the current state of knowledge, the classification in Figure 1 can serve as a useful framework.

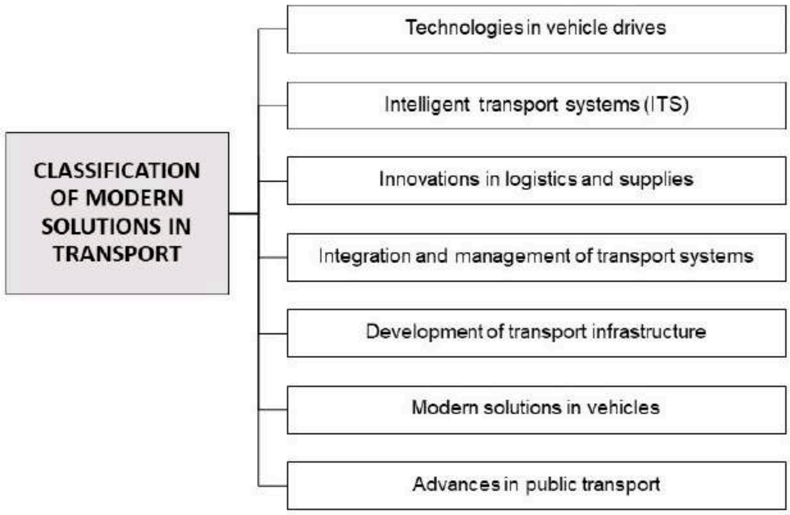

Figure 1. Adopted classification of modern transport solutions.

Recent research results show that vehicle propulsion technology is progressing rapidly, especially in the areas of hybrid (HEV and PHEV) and fully electric (BEV) drivetrains [28,29]. Work is also advancing on autonomous vehicles—those capable of driving and making decisions without human input [30]. Many publications focus on intelligent transport systems (ITS), including traffic management systems [31,32] and advanced technologies that assist with navigation and provide information to road users [33,34]. Innovation in logistics and delivery is also an active area of research, with projects exploring the use of UAVs [35] and autonomous trucks for parcel delivery [36]. Attention is also being paid to the integration and management of transport systems, such as MaaS (Mobility as a Service) platforms [37], real-time public transport management systems [38,39], and smart car parks [40]. A crucial component for the comprehensive development of the transport sector is the supporting infrastructure. This includes research on electric vehicle charging stations, sensors for smart transport systems [41], and integrated transfer hubs [42]. A significant body of literature also addresses modern vehicle technologies, such as the connected car, which enables two-way communication with systems outside the vehicle [43], as well as a range of innovations in advanced driver assistance systems (ADAS) [44]. Another important category includes public transport solutions, particularly efforts toward autonomous urban transport [45] and the implementation of on-demand transport systems [46,47]. Progress is also being made on smart bus stops and stations [48,49].

In this section, specific examples of transport innovations are linked to the identified solution categories, based on a comprehensive literature review. The analysis of research progress considered the alignment of these solutions with the principles of sustainable transport and their importance in the face of potential global crises.

2.2. Characteristics of Global Crises

Before reviewing the research, it is important to establish a theoretical framework that outlines the characteristics of undesirable phenomena, such as global-scale crises. In the literature, the term 'crisis' is defined in various ways. Frazmand [50] provided a basic definition, describing a crisis as an undesirable event resulting from natural, technological, or man-made causes. A crisis is also characterized by widespread negative consequences that can affect entire communities or regions [3,4]. Rodriguez et al. [51] further explained that a crisis occurs when fundamental values, such as safety, security, health, or wealth, are threatened.

Given these definitions, a global crisis can be understood as a situation where problems or threats have an international reach, impacting multiple countries and societies at once. Such a crisis has the potential to destabilize the economy, public health, politics, the environment, or other critical areas on a global scale. It is also emphasized that the recovery period following a crisis can be lengthy and may require coordinated efforts and international cooperation [52,53]. Global crises can be classified in different ways, depending on their causes and the areas they affect. For the purposes of this study, the classification was based on Borca et al. [54], Gundel [55], and Sawada [56], with additional consideration given to military crises, reflecting the geopolitical tensions witnessed in recent years across many regions [57,58] (Table 1).

Table 1. Adopted classification of global-scale crises.

Type of Crisis	Description	Example
Economic crisis	International economic problems that impact the stability of markets, nations, and societies.	• Global financial crisis (2008–2009) [6,59]
Environmental (ecological) crisis	Threats to ecosystems and human health caused by environmental pollution, climate change, and overexploitation of natural resources.	• Global temperature rise [60] • Increasing frequency of extreme weather events [61]
Health crisis	Public health threats from widespread diseases, limited access to healthcare, or events, such as pandemics, epidemics, and natural disasters.	• COVID-19 pandemic (2020) [62,63]
Social crisis	Disruptions in societal functions, such as mass protests, social tensions, growing inequality, or challenges to social integration, leading to destabilization and conflict.	• Migration crisis in Europe (2015) [7,64]
Military crisis	Armed conflicts or the threat of military force destabilizing regions and having global consequences.	• Armed conflict between Ukraine and Russia (2022) [9] • Tensions between Iran and Israel (2024) [65]

Additionally, in order to deepen the characterization of the types of crises considered, a comparative analysis was conducted, which identified the symptoms that distinguish a specific crisis from others and showed the possible disruptions that these events may cause in the transport sector (Table 2).

It is difficult to classify crises in a clear and objective manner. Each crisis may have unique characteristics and varying levels of impact. Additionally, crises often have multiple interconnected causes and effects. For instance, the health crisis triggered by the COVID-19 pandemic had severe global economic consequences [83], while the 2008 financial crisis led to significant social challenges [84]. Military threats can also contribute to crises, as demonstrated by the influx of immigrants to Europe [7]. As shown in Table 1, the early 21st century has been marked by a variety of global crises with diverse origins. This suggests that a range of threats will likely continue to arise in the future, highlighting the need to explore sustainable transport solutions that could prove effective in mitigating potential global crises.

Table 2. Comparison of crisis types and their impact on transport.

Type of Crisis	Distinguishing Symptoms	Impact on the Transport Sector
Economic crisis	• Sharp decline in market values and asset prices, and an increase in unemployment and inflation • Reduction in production and decline in investment and consumption • Bankruptcies, financial problems, and falling incomes at the corporate and individual levels	• Lower demand for travel due to costs [66] • Decrease in freight transport volumes [67] • Society's shift toward public transport [68] • Reducing household expenditure on transport [69]
Environmental (ecological) crisis	• Includes degradation of natural resources (air, water, and soil) • Threat to human health from climate change, smog, and environmental pollution • Visible in the form of damage to the natural environment (forest fires and species extinction) • Related to natural processes (e.g., global warming).	• Limitations on the availability of raw materials for vehicle production [70] • Growing demand for more ecological forms of transport [71] • Rising prices of conventional fuels [72]
Health crisis	• Directly affects the health of the population • Sharp increase in demand for medical services • Rapid spread of diseases (epidemics and pandemics) • The need to apply preventive measures (quarantine and personal protective equipment)	• Decrease in demand for passenger transport, especially public transport [15] • Declining interest in tourist trips [13] • Change of preferences regarding the choice of means of transport [73] • Disruptions in global supply chains and changes in the structures of transported goods [74]
Social crisis	• Destabilizes basic social structures • Weakens the sense of collective identity and social ties • Provokes mass reactions (protests, strikes, and social movements) • Causes social transformation, often influencing subsequent generations	• Declining demand for travel due to safety concerns [75] • Problems with ensuring the safety of transport infrastructure [76] • Inequality in access to transportation [77]
Military crisis	• Direct threat to the lives of the population as a result of military operations • Includes the use of armed forces (troops, weapons, and equipment) • Causes physical destruction of infrastructure • Results in the declaration of martial law and mobilization and in taking action at the state level	• Destruction of transport infrastructure [78] • Air and sea space restrictions [79,80] • Suspension of international connections [81] • Threat of attack on transports [82]

2.3. Assumptions of Sustainable Transport Development

In analyzing the literature on transport solutions, it is essential to consider the concept of sustainable transport development and its key principles. According to the Organization for Economic Co-operation and Development (OECD), sustainable transport is one that does not endanger public health and meets the needs for access consistent with the use of renewable resources below their rates of generation, and use of non-renewable resources below the rates of development of renewable substitutes [85]. The Centre for Sustainable Transportation (CST) provides a more detailed explanation. It states that a sustainable transportation system is one that:

- Allows the basic access and development needs of individuals and societies to be met safely, and with equity within and across generations (social dimension).
- Is affordable, operates fairly and efficiently, and fosters sustainable regional development (economic dimension).
- Limits emissions and waste and minimizes the use of land and production of noise.
- Functions based on a participatory process that includes relevant stakeholders from all parts of society (degree of participation) [86,87].

Dalkmann and Huizenga [88] further emphasized that sustainable transport should limit both short- and long-term negative impacts on local and global environments, feature economically viable infrastructure and operations, and provide safe and secure access for people and goods. Achieving the objectives outlined in these definitions necessitates specific actions focused on developing sustainable transport, which can be categorized into four main areas (Figure 2).

Figure 2. Main areas of action for sustainable transport development.

The principles of sustainable transport development can primarily be implemented through effective management of transport systems. This includes optimizing transport needs and improving the flow of passengers and goods [89,90]. Another key focus is capacity management, which aims to reduce society's reliance on passenger cars. This can be achieved by promoting alternatives, such as public transport, cycling, and walking [91]. Minimizing environmental impacts is also crucial for sustainable transport development, primarily by reducing exhaust emissions, noise, and waste (e.g., oils and batteries) [92,93]. Furthermore, as shown in Figure 2, sustainable transport development can be facilitated by decreasing dependence on fossil fuels (energy management) through the use of electric vehicles, biofuels, or other alternative fuels [94,95].

In this article, transport solutions are analyzed in accordance with the definitions, principles, and areas of action presented in this section. These solutions not only align with the concept of sustainable development but also enhance the level of safety and stability in the transport sector during crisis events.

3. Materials and Methods

In this paper, a systematic literature review was conducted to identify the latest advances in sustainable transport development and to highlight their significance in the context of potential global crises. Four different databases were used for this purpose: Scopus, Google Scholar, DOAJ, and IEEE. The review was conducted between August and October 2024. The systematic review method employed in this publication is based on the approach outlined by Liberati et al. [96], which aligns with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [97]. This methodology is also commonly used in studies by other researchers [54,98–100].

The latest advances in the area of sustainable transport development were classified according to the breakdown detailed in Section 2.1. Global crises were categorized based on Borca et al. [54], Gundel [55], and Sawada [56]. Additionally, military crises were included due to recent geopolitical tensions in various regions around the world [57,58] (Section 2.2). The concept of 'sustainable transport' was clarified with a specific definition provided for this study (Section 2.3). The database search focused on metadata, including titles, abstracts, and keywords. It is important to note that the specific databases differ in their filtering capabilities. Table 3 presents the metadata searched in each database, along with the search records.

Table 3. Metadata searched in selected databases.

Database	Searched Metadata	Entered Search Records
Scopus	Title, abstract, keywords	TITLE-ABS-KEY: (global OR economic OR environmental OR climate OR health OR social OR migration OR military OR pandemic) AND (crisis OR threats) AND (sustainable) AND (transport OR transportation) AND (development OR solution OR advances OR innovation)
Google Scholar	Title, keywords	((intitle: global OR keyword: global) OR (intitle: economic OR keyword: economic) OR (intitle: environmental OR keyword: environmental) OR (intitle: climate OR keyword: climate) OR (intitle: health OR keyword: health) OR (intitle: social OR keyword: social) OR (intitle: migration OR keyword: migration) OR (intitle: military OR keyword:military) OR (intitle: pandemic OR keyword: pandemic)) AND ((intitle: crisis OR keyword: crisis) OR (intitle: threats OR keyword: threats)) AND (intitle: sustainable OR keyword: sustainable) AND ((intitle: transport OR keyword: transport) OR (intitle: transportation OR keyword: transportation)) AND ((intitle: development OR keyword: development) OR (intitle: solution OR keyword: solution) OR (intitle: advances OR keyword: advances) OR (intitle: innovation OR keyword: innvation))
DOAJ	Title, abstract, keywords	((TI: global OR ABS: global OR KEY: global) OR (TI: economic OR ABS: economic OR KEY: economic) OR (TI: environmental OR ABS: environmental OR KEY: environmental) OR (TI: climate OR ABS: climate OR KEY: climate) OR (TI: health OR ABS: health OR KEY: health) OR (TI: social OR ABS: social OR KEY: social) OR (TI: migration OR ABS: migration OR KEY: migration) OR (TI: military OR ABS: military OR KEY: military) OR (TI: pandemic OR ABS: pandemic OR KEY: pandemic)) AND ((TI: crisis OR ABS: crisis OR KEY: crisis) OR (TI: threats OR ABS: threats OR KEY: threats)) AND (TI: sustainable OR ABS: sustainable OR KEY: sustainable) AND ((TI: transport OR ABS: transport OR KEY: transport) OR (TI: transportation OR ABS: transportation OR KEY: transportation)) AND ((TI: development OR ABS: development OR KEY: development) OR (TI: solution OR ABS: solution OR KEY: solution) OR (TI: advances OR ABS: advances OR KEY: advances) OR (TI: innovation OR ABS: innvation OR KEY: innovation))
IEEE	Title, abstract, keywords	("All Metadata": global OR economic OR environmental OR climate OR health OR social OR migration OR military OR pandemic) AND ("All Metadata": crisis OR threats) AND ("All Metadata": sustainable) AND ("All Metadata": transport OR transportation) AND ("All Metadata": development OR solution OR advances OR innovation)

A search of selected databases identified 484 items. Table 4 lists the number of results obtained from each database. In addition, 8 studies from supplementary sources—other databases and results obtained directly through web searches—were included. These publications were considered important, as they deal with transport solutions that can be crucial to enhancing security during environmental, health, and military crises.

Table 4. Number of studies obtained from each database.

Database	Scopus	Google Scholar	DOAJ	IEEE	Other Sources	Sum
Number of studies	161	143	57	123	8	492

The extracted entries were then checked for duplicate searches. A total of 49 duplicate publications were identified and removed from the collection, resulting in 443 studies remaining. Furthermore, additional inclusion and exclusion criteria were applied to the literature review, which were considered when analyzing titles and abstracts (Table 5).

Table 5. Inclusion and exclusion criteria for publications in this literature review.

Inclusion Criteria	Justification
Publication in a peer-reviewed journal	Articles from peer-reviewed journals reflect the current state of knowledge of the scientific community in a given research area
The article describes the latest solutions for the development of sustainable transport	The aim of the study is to identify the latest solutions in the development of sustainable transport and indicate their importance in the event of global crises
Paper presents the possibilities of using modern technologies in transport in the event of crises	
Exclusion Criteria	**Justification**
No full text available	An article is only relevant to the review if the full text is available
The article is not written in English	English is a commonly used language in the scientific community and is, therefore, understandable to the authors
Studies were published before 2020	The study presents recent solutions in transport

After applying the defined inclusion and exclusion criteria, 157 entries were excluded from the review. As a result, 286 studies were extracted as a body of literature for further analysis. In the next stage, another 63 publications were eliminated due to a lack of thematic relevance to the review. Ultimately, 223 studies were gathered for further use in descriptive and thematic analysis. The purpose of the descriptive categories was to extract data from the literature useful for describing and differentiating studies. The thematic categories were used to identify and classify the solutions examined in this publication. Based on the current state of knowledge, seven categories of solutions in the area of sustainable transport development were listed, particularly significant in the context of global threats. This classification structured Section 4.2. The descriptive and thematic categories included in the review are presented in Table 6.

Table 6. Descriptive and thematic categories used to extract data from the literature.

Category Group	Category	Information Obtained
Descriptive (description and differentiation of studies)	Publication date	Year of publication
	Journal	Name of the journal
	Author	Names and surnames of authors
	Title	Full title of the paper

Table 6. *Cont.*

Category Group	Category	Information Obtained
Thematic (classification of solutions)	Technologies in vehicle drives	Information on solutions in the area of sustainable transport development that can increase the stability of the economy and the resilience of the transport sector to potential global crises
	Intelligent transport systems (ITS)	
	Innovations in logistics and supplies	
	Integration and management of transport systems	
	Development of transport infrastructure	
	Modern solutions in vehicles	
	Advances in public transport	

The procedure for selecting publications for the review is illustrated in a flowchart in Figure 3. As mentioned earlier, this procedure follows the PRISMA approach [97], utilized by authors such as Liberati et al. [96] and Borca et al. [54].

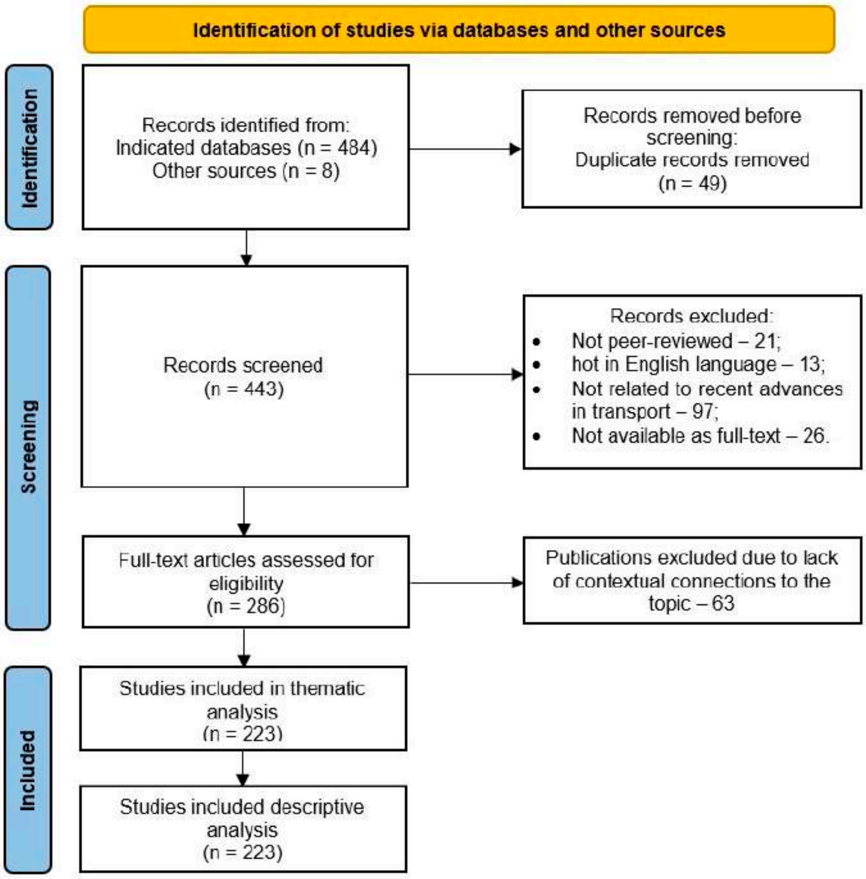

Figure 3. Flowchart for the selection of publications for the literature review.

Ultimately, based on the procedure outlined in this section, 223 scientific publications describing the latest advances in sustainable transport development, particularly relevant in light of global crisis threats, were singled out. The results from this literature review will be presented in the next section of the article (Section 4).

4. Results from the Literature Review

4.1. Recent Advances for the Development of Sustainable Transport

Based on a review of the literature, 223 publications were selected as relevant to the study. Each transport solution was categorized, and relevant literature sources used in the detailed analysis were noted. The findings are summarized in Table 7.

Table 7. Recent transport solutions found as a result of the literature review.

Category	Solution	References
Technologies in vehicle drives	Battery electric vehicles (BEV)	[29,101–111]
	Fuel cell electric vehicles (FCEV)	
	Plug-in hybrid electric vehicles (PHEV)	
	Biofuel-powered vehicles	[112–115]
	Solar-powered vehicles	[116–119]
	Compressed air vehicles	[120–123]
Intelligent transport systems (ITS)	Autonomous vehicles (AV)	[124–131]
	Traffic management systems (TMS)	[31,132–137]
	Emissions' monitoring and control systems	[138–143]
	Real-time mobility management systems	[144–147]
	Smart lighting systems	[148–152]
Innovations in logistics and supplies	Drone-based logistics	[23,153–161]
	Autonomous trucks	[36,162–166]
	The use of blockchain	[167–173]
	Last-mile logistics solutions	[35,174–179]
Integration and management of transport systems	MaaS (Mobility as a Service)	[37,180–187]
	Intelligent fleet management systems	[188–197]
	Real-time public transport management	[38,39,198–202]
	Smart parking systems (SPS)	[40,203–211]
Development of transport infrastructure	Infrastructure for electric vehicles	[212–219]
	Smart roads	[24,41,220–225]
	Green infrastructure in transport	[226–235]
Modern solutions in vehicles	Connected car	[43,236–245]
	Vehicle-to-Everything (V2X)	[188,246–256]
	Advanced driver assistance systems (ADAS)	[44,257–265]
	Modular vehicles	[266–277]
Advances in public transport	Autonomous buses	[45,278–284]
	On-demand public transport	[46,47,146,285–288]
	In-vehicle air quality monitoring systems	[289–296]
	Contactless payment systems	[293,297–302]
	Smart stops and stations	[48,49,303–305]

As shown in Table 7, there are numerous examples of modern transport solutions that align with sustainable development goals while also strengthening economic resilience—particularly within the transport sector—in preparation for potential global crises. The majority of innovations were concentrated in modern vehicle technologies and in the integration and management of transport systems, with 81 out of the 223 papers focusing on these areas. A substantial number of publications also addressed advancements in public transport (35 out of 223 papers) and intelligent transport systems (30 out of 223 papers). Notably, many transport solutions span across categories, reflecting cohesive development efforts within the field. The selected studies provided a basis for a detailed description of the solutions and an analysis of their potential application in crisis scenarios. The findings are discussed in the following section.

4.2. Importance of Recent Solutions in Transport in Case of Global Crises

4.2.1. Technologies in Vehicle Drives

The literature review identified six vehicle drive technologies that align with sustainable development principles and could play a critical role in safeguarding the economy, including the transport sector, during global crises (Table 8).

Table 8. The role of selected solutions in technologies in vehicle drives during potential global crises.

Solution	Role in Case of Potential Crises
Battery electric vehicles (BEV) Fuel cell electric vehicles (FCEV) Plug-in hybrid electric vehicles (PHEV)	• Savings in fossil fuel consumption (economic crisis and environmental crisis) • Reducing pollutant emissions and improving air quality (environmental crisis and health crisis) • Less dependence on fuel imports when using renewable electricity or local hydrogen sources (economic crisis and military crisis) • Useful in military operations where silence and discretion are required (military crisis) • Possibility to carry out transport even when access to traditional fuels is limited due to war operations (military crisis) • Support for the development of more accessible transport systems for society (economic crisis and social crisis)
Biofuel-powered vehicles	• Reduced dependence on oil—less risk of fuel supply interruptions (economic crisis and military crisis) • Reducing emissions and improving air quality (environmental crisis and health crisis) • Possibility of using biofuels in military vehicles (military crisis)
Solar-powered vehicles	• Reducing pollutant emissions and improving air quality (environmental crisis and health crisis) • Lower transportation costs and energy availability for poor regions (social crisis)
Compressed air vehicles	• Lower transportation costs (economic crisis and social crisis) • No lifecycle emissions and improvement of air quality (environmental crisis and health crisis)

BEV, FCEV, and PHEV

Electric drive technologies continue to advance, resulting in several types of vehicles that use electric energy. Battery electric vehicles (BEVs) are fully electric and powered by a battery that is charged from an external source. BEVs eliminate local emissions, significantly reducing CO_2 emissions and improving air quality in urban areas [101]. Fuel cell electric vehicles (FCEVs), similar to BEVs, use electric motors; however, the energy is produced by a reaction between hydrogen and oxygen in a fuel cell, with water being the only byproduct, making FCEVs completely emission-free [102]. Plug-in hybrid electric vehicles (PHEVs) combine the advantages of both electric and combustion engines. The electric motor supplements the combustion engine, and the battery can be charged from external sources (charging stations). PHEVs can run on electric power for short distances, reducing CO_2 emissions, while offering the range of traditional vehicles for long-distance travel [103].

Research on electric drive technologies has primarily focused on extending vehicle range [29,104], increasing battery charging speeds [105], and reducing production costs [106]. Progress in these areas is vital for promoting electric mobility, which can help meet growing transport demands while reducing emissions from the sector [107]. Electric-powered vehicles (BEVs, FCEVs, and PHEVs) not only align with sustainable transport goals but could also be particularly useful in global crises. By relying on electricity as a power source, they reduce the consumption of fossil fuels, supporting long-term preservation of natural resources [108]. In addition, the use of renewable electricity or locally sourced hydrogen can lessen dependency on imports, ensuring transport even when access to traditional fuels is disrupted [109]. Electric vehicles also contribute to the development of more accessible transport systems, which is essential for maintaining mobility in crisis situations [107,110]. Their quiet operation is an additional advantage, especially in military operations that require discretion [111].

Biofuel-Powered Vehicles

Due to the depletion of fossil fuels, undesirable changes in climatic conditions, and increased air pollution, research is being conducted into alternative and sustainable ways to meet energy needs. One such solution is biofuels produced from biomass, which include bioethanol, biodiesel, and biogas. Currently, the fourth generation of biofuels is being developed, involving innovative production methods, such as genetic engineering and nanotechnology, aimed at improving efficiency and reducing production costs [112].

The use of biofuels may be of particular importance in the face of potential crises. Biofuels offer an alternative to fossil fuels, reducing the economy's dependence on oil and thereby lowering the risk of fuel supply disruptions during crises [113]. In addition, biofuel vehicles can reduce greenhouse gas emissions, mitigating the negative impact of transport on climate change and air quality, which in turn supports public health improvements [114]. There are also studies confirming that biofuels can provide an alternative and effective power source for military combat vehicles [115].

Solar-Powered Vehicles

Solar-powered vehicles show great potential as a clean, renewable, and environmentally friendly means of transport. They operate by using photovoltaic panels to generate electricity that powers the vehicle. Research on this technology focuses primarily on extending their range by improving the efficiency of photovoltaic cells and optimizing sunlight exposure while driving [116]. Hybrid systems are also being developed, where solar energy from the panels supplements the battery power of EVs [117]. Solar-powered vehicles produce no harmful emissions, contributing to improved air quality and reducing the environmental impact of transport. Additionally, harnessing renewable solar energy lowers both fossil fuel consumption and reliance on these non-renewable resources [118]. Another key benefit is that solar energy is accessible even in remote, underdeveloped areas, offering a relatively affordable transport solution [119].

Compressed Air Vehicles

A promising technology for achieving zero emissions is the use of compressed air drive systems. Vehicles powered by this method operate by converting the internal energy of compressed air into mechanical energy [120] and can be powered either solely by compressed air or in combination with other fuels, such as gasoline or diesel [121]. Unlike traditional power systems, compressed air does not contribute to environmental degradation or emit harmful compounds into the atmosphere. Additionally, compared to fully electric and hydrogen-powered vehicles, compressed air systems do not generate the pollution associated with battery production and fuel cell disposal, making them a more environmentally friendly option throughout their entire lifecycle [122]. Research also indicates that using compressed air as a supplementary power source can significantly reduce conventional fuel consumption, leading to lower transport costs [123].

4.2.2. Intelligent Transport Systems (ITS)

Through an analysis of recent research advancements, five examples of transport solutions were identified within the intelligent transport systems (ITS) category. These solutions align with sustainable transport principles and hold significant potential for mitigating global crises (Table 9).

Table 9. The role of selected solutions in intelligent transport systems (ITS) during potential global crises.

Solution	Role in Case of Potential Crises
Autonomous vehicles	• Reducing greenhouse gas emissions and the potential for air quality improvement (environmental crisis) • Increased customer service level and reduced logistics costs in enterprises (economic crisis) • Possibility of contactless delivery of goods, including medicines and medical equipment (health crisis) • Use for evacuation of the wounded or as combat vehicles (military crisis)
Traffic management systems	• Reduction of transport congestion—decrease in fuel consumption, shorter travel times, and reduction of exhaust emissions (economic crisis and environmental crisis) • Reducing the risk of collisions and accidents (economic crisis and health crisis) • Social distancing support (health crisis) • Possibility of giving passage priority to emergency vehicles (health crisis and social crisis) • Improving the evacuation of the population from cities (military crisis and social crisis)
Emission monitoring and control systems	• Reducing greenhouse gas emissions and improving air quality (environmental crisis and health crisis) • Possibility of taking immediate action to reduce excessive exhaust emissions and improve the condition of the atmosphere (environmental crisis and health crisis)
Real-time mobility management systems	• Reducing congestion and improving the economic efficiency of the entire transport system (economic crisis) • Reducing fossil fuel consumption and carbon dioxide emissions (environmental crisis) • Application in the maintenance of social distancing and the planning of transportation demand (health crisis) • Support for the coordination of ambulance traffic (social crisis and health crisis)
Smart lighting systems	• Reducing electricity consumption—decreasing greenhouse gas emissions and lower expenses for energy (environmental crisis and economic crisis) • Increasing the level of safety with proper lighting (economic crisis, social crisis, and health crisis)

Autonomous Vehicles (AV)

Advances in technology are transforming traditional transport into fully functional, intelligent machines. These vehicles, equipped with sophisticated systems, can sense their surroundings, connect to networks, make decisions, and travel independently, while ensuring pedestrian and passenger safety. Autonomous vehicles (AVs) represent the current pinnacle of intelligent transport development [124]. Studies indicate that widespread adoption of AVs, particularly electric autonomous vehicles (AEVs), could play a substantial role in sustainable development by reducing greenhouse gas emissions by up to 34% of total transport emissions by 2050 [125]. Moreover, AVs have the potential to improve urban air quality by lowering NOx and CO_2 levels, which is essential for maintaining public health [126]. Research also suggests that AVs integrated with IoT technology could enhance customer service and reduce logistics costs, aiding businesses in navigating economic crises [127]. Additionally, autonomous vehicles offer advantages in times of pandemic by enabling contactless delivery of essential goods, such as medicine and medical equipment [128,129]. In the context of armed conflicts, they could be valuable for evacuating injured individuals from conflict zones [130] or even serving as combat vehicles [131].

Traffic Management Systems (TMS)

Intelligent traffic management systems offer a solution to urban traffic congestion by relying on advanced technological infrastructure, which leverages innovations, such as the Internet of Things (IoT), vehicular ad hoc networks (VANET), cloud computing, 5G connectivity, and Big Data. These systems support traditional traffic management methods while effectively reducing congestion [132]. Reducing traffic jams leads to decreased fuel consumption, shorter travel times, and improved road safety, all of which positively impact the economy [133]. Some proposals suggest expanding these systems to include UAV traffic monitoring, which could reduce the risk of collisions and accidents, thereby benefiting public health and offering cost savings [134]. Studies also highlight the utility of TMS during health crises, such as pandemics, as they can facilitate social distancing by managing traffic flow and optimizing transport resources [135], even prioritizing emergency vehicles, such as ambulances [31]. Additionally, intelligent traffic management aligns with sustainable transport goals by reducing vehicle idle time, thereby lowering fuel consumption and greenhouse gas emissions [136]. TMS also become valuable in crises that require rapid urban evacuation, such as armed conflicts or social unrest [137].

Emissions' Monitoring and Control Systems

Transport has a significant environmental impact, producing noise and pollutant emissions that degrade air quality and contribute to climate change. Modern technologies provide opportunities to sustainably develop this sector, helping to reduce its adverse effects on the climate. Intelligent emissions' monitoring and control systems offer a solution for tracking, analyzing, and managing transport-related pollution. These systems use integrated technologies, including advanced sensors, artificial intelligence (AI), and the Internet of Things (IoT), to enable real-time data collection and analysis. Besides monitoring emissions, such as carbon dioxide, nitrogen oxides, and particulate matter from vehicle exhaust, these systems assess air quality and noise levels [138]. Continuous monitoring and real-time reporting facilitate swift interventions to curb greenhouse gas emissions [139,140], which is crucial for mitigating global warming and addressing the environmental crisis. Emissions' monitoring and control systems are also vital in health crises, where air quality is critical for public health [141]. During the COVID-19 pandemic, these systems were widely implemented, helping to reduce pollution levels and potentially influencing disease outcomes [142,143].

Real-Time Mobility Management Systems

Addressing urban challenges with AI-based traffic management solutions, cities are exploring real-time traffic management systems to optimize routing and ease congestion. These systems are supported by applications that allow users to select from various transportation modes and routes on a single platform (known as mobility on demand). This innovative traffic management approach aims to reduce congestion, enhance travel time reliability for commuters, and improve the economic efficiency of transport systems, which is particularly valuable during sudden economic disruptions [144]. In addition, AI-supported management, coupled with Internet of Things (IoT) capabilities, enables real-time route planning and reduces fuel consumption through congestion relief—making it an approach aligned not only with sustainable transport goals but also with environmental crisis management [145]. Studies suggest this innovative approach could also play a role in health crises, such as pandemics, by supporting social distancing and optimizing transport demand [146]. Moreover, this solution could support the coordination of ambulance traffic, providing significant public health benefits [147].

Smart Lighting Systems

Proper lighting is essential for visibility, which greatly enhances travel comfort and road safety. However, streetlight operation requires substantial energy, incurring significant costs and environmental impacts. Consequently, extensive research is directed toward improving the efficiency of lighting systems [148]. Advances in both wired and wireless networks, control technologies, and embedded systems now allow for modern lighting solutions that minimize energy consumption. Smart lighting systems, which can automatically adjust light intensity in real time based on current needs (e.g., traffic volume, time of day, and weather conditions), are increasingly regarded as key tools for reducing energy waste and, in a broader perspective, for limiting greenhouse gas emissions [149]. Moreover, IoT-enabled smart lighting systems, supported by advanced control units, can lower electricity costs—a particularly valuable benefit when financial resources are constrained [150,151]. Research also highlights that these systems allow for optimal lighting of critical zones, such as bus stops, transit stations, and pedestrian crossings, facilitating crowd management, reducing accident risk, and enhancing overall urban safety, especially at night [152].

4.2.3. Innovations in Logistics and Supplies

Recent advancements in logistics and supply chains align with principles of sustainable transport and hold potential as critical responses to global crises. A literature review identified four notable examples of such innovations (Table 10).

Table 10. The role of selected innovations in logistics and supplies during potential global crises.

Solution	Role in Case of Potential Crises
Drone-based logistics	• Increased efficiency of logistics, thanks to automated deliveries and shortened transport times (economic crisis) • Reducing the use of conventional fuels and greenhouse gas emissions (environmental crisis and health crisis) • Possibility of quick and contactless delivery of medicines, personal protective equipment, and vaccines (health crisis) • Support of emergency medical systems and efficient transport of essential resources—medicine, food, and water (social crisis and military crisis)
Autonomous trucks	• Reducing carbon dioxide emissions and improving air quality (environmental crisis and health crisis) • Increasing the efficiency of supply chains and reducing operating costs thanks to the ability to quickly respond to prevailing road conditions, reducing fuel consumption and eliminating the employment of drivers (economic crisis) • Use of autonomous convoys to safely deliver resources to dangerous areas (social crisis and military crisis)
The use of blockchain	• Ensuring transparency, traceability, and reliability of the entire supply chain—effective resource management (economic crisis) • Monitoring the transport of medical supplies and devices, as well as patient records (health crisis) • Tracking the location and level of pollutant emissions in supply chains and ensuring transparency regarding the sustainable activities of companies (environmental crisis and health crisis) • Monitoring supplies to threatened areas and supervising the distribution of resources (social crisis and military crisis) • Reducing the risk of errors, delays, and other logistical challenges that may significantly affect the success of an operation (military crisis)
Last-mile logistics solutions	• Reducing delivery costs through automation, route optimization, as well as reducing expenditure on salaries, fuel, and vehicle operation (economic crisis) • Reducing urban congestion and minimizing carbon dioxide emissions (environmental crisis and health crisis) • Ensuring continuity of supply during mobility restrictions and the safe and contactless delivery of essential goods (health crisis)

Drone-Based Logistics

Drones, or unmanned aerial vehicles (UAVs), are compact aircraft that can be equipped with various devices, including cameras, thermal sensors, GPS, communication systems, and specialized tools. These devices support tasks such as environmental monitoring, technical inspections, parcel delivery, and emergency response operations. The primary advantage of drones is their ability to access and navigate challenging and remote areas with ease [23], positioning them as promising assets for logistics and delivery solutions that promote sustainable development and provide valuable support during global crises. For businesses and governments, drones offer an innovative method to enhance logistics efficiency, enabling automated deliveries, reducing transport times, and lowering fuel consumption, which collectively reduce operational costs [153,154]. Studies indicate that, in comparison to traditional vehicles, electric UAVs can significantly cut greenhouse gas emissions, contributing positively to environmental sustainability [155]. Drones have also proven valuable during health crises, as evidenced during the COVID-19 pandemic, where they enabled efficient, contactless delivery of medications, SARS-CoV-2 tests, personal protective equipment, and even vaccines [156–158]. The literature further highlights UAV-based logistics as a vital resource in humanitarian aid during natural disasters, social conflicts, and even armed conflicts. In such scenarios, drones effectively support emergency medical systems [159] and the transportation of essential resources, such as medications, food, and water [160,161].

Autonomous Trucks

Autonomous trucks are equipped with technology that enables driverless cargo transport. Using advanced systems, such as artificial intelligence (AI), sensors, cameras, LIDAR data, and GPS, these vehicles can independently navigate roads, plan routes, and make safety-related decisions [36,162]. Progress in autonomous truck technology can substantially improve the efficiency of logistics and supply chains while reducing the environmental impact, aligning with sustainable transport objectives. When paired with electric or hybrid engines, autonomous trucks can also cut CO_2 emissions, supporting climate action efforts and improving air quality [163]. Autonomous trucks provide the benefit of real-time control over driving parameters and rapid responsiveness to changing road conditions, resulting in lower fuel consumption, resource conservation, and cost savings for transport companies. Without the need for drivers, these vehicles can operate continuously, reducing transport times and enhancing supply chain efficiency [164]. Research into autonomous convoys also underscores their potential in military or humanitarian crisis settings. Fully autonomous convoys can deliver essential supplies to areas where traditional transport is unsafe or inaccessible, thereby increasing logistics safety in high-risk areas and minimizing human exposure to risk [165,166].

The Use of Blockchain

Blockchain technology enables decentralized data storage and transfer without intermediaries or a central system. As a digital ledger, blockchain is made up of interconnected blocks that record transactional information, with each block containing data from the previous one, forming a secure chain [167]. In logistics and transport, blockchain allows for fast, transparent tracking of goods flow, reducing risks of fraud, counterfeiting, and administrative errors. Its transparency, traceability, and reliability allow companies to manage resources effectively, reduce costs, and maintain stability in times of economic uncertainty [168]. This technology has also demonstrated its value in health crises, such as during the COVID-19 pandemic, by enabling secure tracking of medical supply chains, equipment, and patient records [169]. Blockchain further supports eco-friendly practices in supply chains by enabling tracking of location and pollution data (primarily CO_2), which enhances transparency in corporate sustainability efforts [170]. Blockchain's role in humanitarian aid is also significant, providing precise tracking of deliveries to at-risk areas and ensuring resources are fairly distributed to those in need [171,172]. In military logistics, blockchain can offer secure, transparent tracking of supplies and equipment, reducing the risks of errors, delays, and other logistical challenges that could affect mission success [173].

Last-Mile Logistics Solutions

Last-mile logistics represents the final step in delivering goods from a warehouse or distribution center to the end consumer. This area faces numerous challenges today, including growing volumes of goods, time constraints, rising costs, an aging workforce, and sustainability concerns [174]. Emerging solutions include autonomous vehicles, alternative transport methods, and distributed warehousing systems. Technologies such as UAVs and small unmanned ground vehicles (SUGVs) reduce delivery costs through automation, route optimization, and lower expenses for wages, fuel, and vehicle maintenance, supporting the financial stability of businesses [35]. The use of UAVs, light electric freight vehicles (LEFV), and alternative transport modes, such as electric cargo bikes or tricycles, also helps alleviate urban congestion and reduce carbon emissions, advancing sustainable development goals. Compared to traditional delivery vehicles, these options require less road space and offer greater ease of access and parking [175,176]. Studies further underscore the importance of last-mile logistics innovations for public health. Solutions such as delivery networks of cooperating unmanned ground vehicles (UGVs) [177] or the transport of medicines, food, and healthcare supplies by drones or autonomous robots have proven invaluable during public health crises. During the COVID-19 pandemic, these technologies enabled safe, rapid, and contactless delivery of essential goods, reducing infection risks and maintaining supply chain continuity despite movement restrictions [178,179].

4.2.4. Integration and Management of Transport Systems

The literature review highlighted four solutions that advance sustainable transport development and can play a crucial role in global crises (Table 11).

Table 11. The role of selected solutions in the integration and management of transport systems during potential global crises.

Solution	Role in Case of Potential Crises
Mobility as a Service (MaaS)	• Reducing carbon dioxide emissions and air pollution (environmental crisis and health crisis) • Lower transport costs for users and reduction of expenditure on the provision of transport services by enterprises (economic crisis) • Possibility to limit interpersonal contacts and maintain social distancing by renting individual means of transport, as well as the option to book a ride and make contactless payments (health crisis)
Intelligent fleet management systems	• Possibility to control the implementation of transport services in terms of route and schedule compliance, monitor traffic violations, and supervise the way the vehicle is driven (economic crisis) • Monitoring vehicle traffic and checking drivers' compliance with sanitary rules and optimizing routes in terms of traffic disruptions and intensity (health crisis) • Possibility of using it to manage emergency vehicles (health crisis, social crisis, and military crisis) • Reducing exhaust emissions and improving air quality (environmental crisis and health crisis)
Real-time public transport management	• Reduction of costs and travel times for passengers and lower expenditure on transport by enterprises (economic crisis) • Reducing carbon dioxide emissions and environmental pollution (health crisis and environmental crisis) • Ability to respond quickly to the current occupancy of running vehicles—minimizing congestion and maintaining social distancing (health crisis)

Table 11. *Cont.*

Solution	Role in Case of Potential Crises
Smart parking systems	• Reduction of costs and time associated with vehicle parking (economic crisis) • Reducing greenhouse gas emissions and improving air quality in cities (environmental crisis and health crisis) • Reducing human interaction through cashless payments and remote parking reservations (health crisis) • Possibility of using parking lots as vaccine distribution centers (health crisis)

Mobility as a Service (MaaS)

Mobility as a Service (MaaS) is an innovative concept that greatly enhances transport integration by offering a unified solution to the diverse range of transport options available. MaaS is an integrated platform that combines public, private, and shared transport modes, allowing users to not only find the best travel option for their needs but also to pay for their entire journey as a single, seamless service. The decision-making process is simplified and managed conveniently through a single mobile application [180].

MaaS is consistently evolving to provide safe and sustainable mobility solutions to the population, which in turn promotes its widespread adoption and social acceptance. One of the key directions of development is the inclusion of the Sustainable Development Goals (SDGs), which allows transforming this platform into an even more environmentally friendly one, i.e., sustainable MaaS (S-MaaS) [181]. Research shows that integrating multiple transport modes, particularly electric and shared mobility options (e.g., car sharing and bike sharing), can significantly lower carbon dioxide emissions and reduce air pollution. This is especially relevant in addressing environmental crises, such as global warming, as it mitigates transport's impact on the climate and promotes eco-friendly travel options [182,183]. MaaS also offers economic resilience by reducing transport costs. For consumers, it minimizes personal vehicle expenses and provides cost-effective alternatives for daily travel. For companies, the rising demand for shared services, such as car sharing, urban bike rentals, and integrated public transport, helps reduce fleet maintenance costs by spreading expenses across multiple users [184–186]. Research also suggests that Mobility as a Service can be effective in health crises, as seen during the COVID-19 pandemic. Key benefits include reduced interpersonal contact and the ability to maintain social distancing by using rented, individual transport options. Booking and contactless payment options further enhance safety for users [37,187].

Intelligent Fleet Management Systems

Companies that operate vehicle fleets—such as trucks, delivery vehicles, taxis, and buses—must prioritize efficient use and management of their transport assets to maintain competitiveness. Intelligent fleet management systems provide critical support by employing advanced technologies, such as IoT, cloud computing, and Big Data, to optimize vehicle operations, track usage, and enable real-time decision-making [188,189]. These systems enhance transport service control by ensuring adherence to routes and schedules and monitoring traffic violations, thereby improving both passenger service quality and road safety. Additionally, they monitor driver speed and driving behavior, contributing to lower fuel consumption and reduced operational costs [190–192]. During health crises, intelligent fleet management systems are invaluable for tracking vehicle movement and monitoring drivers' compliance with sanitation protocols, ensuring safe and timely transport of essential goods, such as medicines and medical supplies. The system also allows for route optimization and real-time vehicle updates, taking into account obstacles and traffic density [193,194], which helps minimize interpersonal contact—a critical factor in pandemics. Furthermore, these systems can be adapted to manage emergency vehicles, offering benefits such as route planning, access to patient information, accident detection, driver distraction recognition, and additional support tools [195]. In environmental crises, intelligent fleet management reduces emissions through route optimization and fuel-saving measures [190]. When integrated with electric vehicle fleets, these systems are particularly eco-friendly, especially when optimal energy management and advanced charging strategies are used [196,197].

Real-Time Public Transport Management

The development and deployment of intelligent, real-time public transport management systems are rapidly advancing in urban areas, particularly those with complex transport networks. These systems utilize a suite of interconnected technologies, including the Internet of Things (IoT), Big Data, artificial intelligence (AI), cloud computing, and edge computing. This integration provides real-time insights into public transport operations by enabling data collection, integration, and processing across intelligent traffic infrastructures and VANET [38,198]. Research highlights the benefits of such systems, particularly for bus transport, where optimized route selection and scheduling can lower operational costs, reduce travel times for passengers, generate economic benefits for operators, cut CO_2 emissions, and promote environmental sustainability [199]. Buses serve as a vital component of sustainable urban mobility; however, their travel times are significantly affected by street congestion [39]. Real-time passenger information systems address this challenge by providing travelers with updated arrival times, potential delays, and schedule modifications, enabling more efficient journey planning and reducing wait times at stops [200]. Another benefit of real-time public transport management lies in its adaptability to passenger demand, allowing for dynamic schedule adjustments that minimize overcrowding and support social distancing—a feature particularly valuable during health crises, such as the COVID-19 pandemic [201,202].

Smart Parking Systems (SPS)

Traditional parking practices often lead to inefficiencies, including congestion caused by drivers searching for available spaces and challenges in revenue management for operators. Smart parking systems (SPS) address these issues by providing real-time information on parking spaces' availability, optimizing space utilization, and offering streamlined payment options. SPS comprises multiple interconnected technological components that collectively enhance car park management and user satisfaction. Key elements include occupancy sensors in parking spaces, a data communication network, a data management system for processing and analysis, and a user application [40,203]. Smart parking systems reduce parking-related costs for cities and drivers alike by automating and optimizing parking processes, thus promoting better space utilization, decreased vehicle traffic, and lower management expenses. The ability for users to reserve spaces, navigate to locations, and pay via an app saves time and fuel [204,205]. These systems also hold environmental relevance by mitigating congestion [206] and reducing the time required to find a parking space, thereby lowering greenhouse gas emissions from vehicle exhaust [207]. Studies also indicate that integrating smart parking systems with the electric vehicle (EV) charging infrastructure increases the availability of charging stations, improves user convenience, and supports sustainable transport development [208,209]. SPS can also play a critical role in health crises by minimizing human interaction through cashless payments and remote reservations [210]. Furthermore, smart parking areas can be repurposed as distribution centers for vaccines, facilitating efficient vaccination processes [211].

4.2.5. Development of Transport Infrastructure

Infrastructure plays a foundational role in any transport system, supporting both existing and future solutions. A review of the literature identified three primary research areas in transport infrastructure, with a focus on sustainable development and adaptability during global crises (see Table 12).

Table 12. The role of transport infrastructure solutions in case of potential global crises.

Solution	Role in Case of Potential Crises
Infrastructure for electric vehicles	• Support for the electrification of transport and positive influence on EV purchasing decisions (economic crisis and environmental crisis) • Reducing greenhouse gas emissions and improving air quality, especially in cities (environmental crisis and health crisis) • Opportunity to reduce dependence on fossil fuels through the use of renewable energy (economic crisis and environmental crisis)
Smart roads	• Optimization of transportation, improvement of vehicle flow, reduction of fuel consumption, and increase of supply efficiency (economic crisis and environmental crisis) • Improving road safety (economic crisis, health crisis, and social crisis) • Maintaining the appropriate state of the transport network (economic crisis, health crisis, social crisis, and military crisis) • Reduction of energy consumption and pollutant emissions (environmental crisis and health crisis) • Monitoring traffic and providing real-time information (health crisis) • Possibility to control ongoing transports (military crisis)
Green infrastructure in transport	• Reducing the harmful impact of transport on the environment—lower greenhouse gas emissions and improving air quality (environmental crisis and health crisis) • Positive impact on the mental and physical health of society due to the possibility of safe and comfortable travel by bicycle or on foot (health crisis) • Reducing dependence on traditional means of transport—decreasing road congestion and consumption of conventional fuels (economic crisis and environmental crisis)

Infrastructure for Electric Vehicles

The electrification of transport is a prominent focus in recent studies. Electric vehicles (EVs) are increasingly accepted by the public, steadily growing their market share. Key factors influencing EV popularity include driving range, as well as the convenience and cost of energy supply—both of which largely depend on the availability and strategic placement of charging infrastructure [212]. Research underscores the importance of government financial support for initiatives such as fast-charging stations, which are essential to the wider adoption of EVs, fostering economic growth and promoting sustainability [213]. Expanding EV infrastructure, particularly through an accessible charging network, has a direct impact on consumer purchasing decisions and supports EV adoption [214]. The resulting rise in EVs on the roads, facilitated by adequate charging access, can significantly reduce exhaust emissions, contributing to improved air quality [215], which is especially critical in urban centers with severe pollution issues. As shown in [216], the electrification of transport can reduce harmful airborne pollutants, a vital factor for public health. Other studies suggest that the environmental and health impacts of transport could be further minimized through the integration of renewable energy sources, V2G technology, and smart charging systems [217]. These approaches not only reduce greenhouse gas emissions but also lessen reliance on fossil fuels [218], a key consideration in the face of potential supply disruptions. The literature also highlights the need for equitable development of EV infrastructure, extending coverage to less affluent areas [219], where electrification can improve quality of life and reduce social inequalities.

Smart Roads

Smart roads employ IoT technology, combining physical infrastructure, such as sensors, cameras, LED lighting, and solar panels, with advanced software solutions, such as AI or Big Data [220]. The concept of smart roads enhances existing road systems to meet contemporary mobility demands, facilitating more efficient transport and vehicle flow, reducing fuel consumption, and improving delivery logistics. These developments provide financial advantages to both businesses and road users while simultaneously supporting sustainable development [221]. In [222], it is additionally pointed out that IoT-based smart roads, integrated with connected autonomous vehicles (CAVs), may enhance traffic safety and the efficiency of transport systems in the future. Other research highlights the ability of smart roads to monitor road surface conditions, warn of hazardous driving conditions, and even report possible maintenance needs or damage [223]. These features are essential not only for user safety but also for maintaining road conditions, particularly in crisis situations. Smart roads also reduce the environmental impact of transport. Study results reveal substantial reductions in energy consumption, pollution, and accident rates on smart highways relative to traditional roadways [224]. Electric road systems (ERS), which power EVs in transit, present additional environmental advantages by providing greater flexibility and convenience for drivers, eliminating the need to stop for charging [225]. The literature also emphasizes the benefits of IoT and machine learning technologies used in smart highways. These roads allow real-time information sharing with drivers, monitor traffic conditions, and provide alerts on potential congestion or incidents [24], which can be crucial for emergency transports. Furthermore, smart roads may have military applications, where WSNs positioned along roadways allow for continuous monitoring to secure transport safety [41].

Green Infrastructure in Transport

The primary aim of green transport infrastructure is to enhance mobility while minimizing the environmental impact of transport. Sustainable travel options, such as cycling and walking, allow individuals to reduce pollution significantly. Cycling, in particular, offers several advantages, including the ability to avoid traffic congestion, eliminate harmful emissions, reduce reliance on non-renewable resources, and promote physical fitness. Additionally, cycling incurs no fuel costs and minimal ongoing costs, making it an economically viable mode of transport. It also enhances road safety by decreasing the volume of cars. However, a well-developed network of bike paths is essential to ensure both safety and comfort for cyclists [226]. A similar argument applies to walking. Research highlights that pedestrian-friendly infrastructure—designed to be safe, continuous, and accessible to a wide range of users—can significantly reduce car traffic in urban areas, thereby reducing air pollution and noise levels [227,228]. Additional examples of green transport infrastructure cited in the literature include innovative measures, such as photovoltaic noise barriers [229], bus stop roofs covered with vegetation [230], and corridors designed for both wildlife and pedestrians [231]. Each of these solutions contributes to reducing the environmental footprint of transport. In times of health crises, green infrastructure becomes particularly valuable. Studies have shown that opportunities for outdoor recreation and physical activity were crucial for maintaining mental and physical health during the COVID-19 pandemic [232]. Consequently, walking and cycling became essential for public well-being. This underscores the need for strategic planning and development of urban infrastructure to prepare for future crises [233]. The pandemic also highlighted the increased importance of bike sharing, which emerged as a relatively safe, alternative mode of transport [234]. Furthermore, the literature underscores the role of inclusive spatial planning to ensure that green infrastructure is accessible to all social groups, thereby avoiding inequities and fostering inclusivity [235].

4.2.6. Modern Solutions in Vehicles

A comprehensive literature review identified four key innovations in vehicle technology that not only align with sustainable development principles but could also play a vital role in bolstering the economy and transport sector amidst potential global crises (Table 13).

Table 13. The role of modern solutions in vehicles in case of potential global crises.

Solution	Role in Case of Potential Crises
Connected car	• Lowering transportation costs and increasing road safety (economic crisis) • Reducing pollutant emissions and improving air quality (environmental crisis and health crisis) • Possibility of contactless and coordinated deliveries of goods (health crisis) • Monitoring the health of passengers (health crisis) • Automatic detection and reporting of vehicle failures (military crisis and social crisis)
Vehicle-to-Everything (V2X)	• Optimization of vehicle flow, reduction of fuel consumption, increase of safety of road users, and creation of jobs (economic crisis) • Reducing dependence on oil, coal, and other raw materials (economic crisis, environmental crisis, and military crisis) • Ability to exchange information on the population's health status (health crisis) • Assistance in maintaining social distancing by enabling optimal allocation of passengers to vehicles (health crisis) • Support in medical transports and rescue missions (health crisis and social crisis) • Reliable, high-speed communications between ground and air means of transport (military crisis)
Advanced driver assistance systems (ADAS)	• Improving the flow of vehicles and reducing transportation costs (economic crisis) • Increasing road safety (economic crisis and health crisis) • Lowering pollutant emissions, improving air quality, and reducing the use of resources for the production of spare parts or vehicles (environmental crisis and health crisis)
Modular vehicles	• Reduction of operating costs—lower fuel consumption, increased service level, and reduced travel and waiting times (economic crisis) • Minimizing the harmful impacts on the environment (environmental crisis) • Possibility to adjust the number of available places to current demand (health crisis) • Support for medical and emergency transports (health crisis and social crisis) • Possibility of adapting military vehicles to changing conditions (military crisis)

Connected Car

A connected car is an advanced technology that allows vehicles to communicate in real time with the Internet, other devices, mobile applications, and cloud platforms. This connectivity expands possibilities, transforming the driving experience and providing benefits to drivers, passengers, and manufacturers alike [43]. Aligned with sustainable transport principles, this technology also has potential applications in responding to global crises. These vehicles provide real-time road condition updates, optimize routes, reduce congestion, and relay safety alerts. Connected car technology also enables remote vehicle management, diagnostics, and advanced driver assistance systems (ADAS). By enhancing traffic efficiency and safety, connected vehicles can help reduce transport costs and play a critical role in economic resilience [236,237]. Studies highlight the benefits of connected vehicles in organized truck convoys, potentially reducing operational costs through fuel and route efficiency [238]. This technology also serves as a foundation for connected autonomous vehicles (CAVs), which could address key road transport challenges related to safety, mobility, and environmental impact [239]. Connected vehicle systems also support environmental health, as smoother traffic flow and fewer congestion points lead to lower emissions of carbon dioxide and nitrogen oxides (NOx). Research confirms these benefits for both CAVs [240,241] and diesel vehicles [242,243]. In public health contexts, connected vehicles facilitate contactless and coordinated deliveries of essential items, such as medical supplies and food, which is critical during epidemic situations [236]. Enhanced with additional detection systems, connected vehicles can also monitor passenger health, improving safety and reducing disease spread in society [244]. Connected vehicles also have the capability to automatically detect and report issues, whether in military convoys or humanitarian missions [245], enhancing overall efficiency and significantly boosting the likelihood of successful logistical operations.

Vehicle-to-Everything (V2X)

Vehicle-to-Everything (V2X) is a next-generation technology, designed to connect vehicles with their entire surroundings, making them integral components of the IoT. Unlike traditional connected car technology, V2X enables real-time communication with other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), networks (V2N), and various electronic devices. The V2X system aims to enhance road safety for all users, optimize route efficiency, and support environmentally friendly driving choices [246]. Given its advanced capabilities, Vehicle-to-Everything could serve as a valuable resource in crisis scenarios. This breakthrough technology has the potential to revolutionize global transport networks, and when integrated with complementary innovations, V2X could further drive economic growth and sustainability [247,248]. The potential of V2X to enhance traffic flow, improve road safety, and support sustainable transport development is frequently highlighted. By enabling real-time data exchange between vehicles and their surroundings, V2X can prevent accidents [188], streamline traffic flow, and lower exhaust emissions [249], thus contributing to a safer, more efficient, and eco-friendly transport ecosystem [250]. Furthermore, integrating V2X with electric vehicles could reduce reliance on fossil fuels and create new job opportunities within the green energy sector [251]. Studies emphasize the significant role of 5G-based Vehicle-to-Everything (C-V2X) in public health, as it facilitates the exchange of health-related data, assisting communities in managing viral outbreaks [252]. Another study found that V2X can help optimize vehicle occupancy, supporting social distancing protocols [253]. Research also underscores the importance of Vehicle-to-Everything in medical and rescue transport by alerting other road users to approaching emergency vehicles [254], while dynamically optimizing routes and reducing congestion to facilitate faster response times [255]. Moreover, V2X supports military applications by providing robust, high-speed communication between ground and airborne means of transport, crucial for responsive operations in dynamic settings [256].

Advanced Driver Assistance Systems (ADAS)

Advanced driver assistance systems (ADAS) are a collection of numerous features that enhance vehicle handling while also improving safety. These systems, depending on the manufacturer, level of advancement, and built-in functions, may include a range of sensors and cameras. Key ADAS functions include lane-keeping assist, emergency braking, traffic sign recognition, driver attention monitoring, adaptive cruise control, and blind-spot warning. With these capabilities, ADAS can effectively monitor, enforce, or correct vehicle behavior on the road [44]. ADAS can be particularly significant from an economic perspective. Research has shown that their use can improve vehicle flow on highways and reduce travel costs due to lower fuel consumption [257]. Other studies have highlighted ADAS' role in shaping driving behavior, which also results in reduced fuel consumption [258]. Adaptive cruise control and lane-keeping assist are particularly beneficial in truck convoys, enabling them to respond simultaneously to changing road conditions, which improves safety and reduces transport costs [259]. Publications particularly emphasize ADAS' role in enhancing road traffic safety by reducing the frequency and severity of accidents [260,261]. This is especially important, as a lower number of such incidents can reduce public expenditures on addressing their consequences, including infrastructure repairs, rescue services, administrative costs, and hospitalizations [262]. ADAS can also positively impact the environment due to their potential to optimize vehicle speed and reduce fuel consumption. This can limit pollutant emissions, thereby improving air quality [263,264]. Furthermore, given ADAS' essential role in reducing road accidents, it is worth noting that they not only lessen the social and economic consequences of these events but also reduce resource demand. A lower number of incidents can contribute to sustainable development by reducing the need for spare parts or new vehicles, leading to decreased resource extraction and fewer production processes, which translates to lower CO_2 emissions and water savings [265].

Modular Vehicles

Modular vehicles are those with interchangeable components. This modularity is intended to facilitate repairs and maintenance or enable vehicle reconfiguration to adapt it for specific functions. This solution finds application across various industries and sectors, contributing to increased transport efficiency while reducing its harmful impact on the environment [266]. Publications primarily emphasize the importance of modular vehicles in the context of economic benefits related to transport [267], both for cargo and passenger services [268]. By adjusting the vehicle size to real-time needs through module detachment, carriers can cut operational costs. In urban settings, this approach can reduce travel times, fuel consumption, and operational expenses [269]. Additionally, modular vehicles enhance service quality, as they can swiftly reach destinations and seamlessly connect without requiring stops or transfers [270,271]. Studies confirm the environmental benefits of modular vehicles, particularly electric models, over their entire lifecycle [272,273]. This adaptability proves crucial during crises that disrupt transport demand, such as the COVID-19 pandemic [274]. Research also emphasizes the utility of modular vehicles in medical transport, where their customizable structure reduces response times and allows for configuration tailored to specific emergencies [275]. Furthermore, modular vehicles are highly beneficial in military operations. Their design allows for rapid assembly, disassembly, and reconfiguration, enabling fleets to adapt to changing battlefield conditions with greater flexibility and efficiency [276,277].

4.2.7. Advances in Public Transport

Public transport systems are continuously evolving to better meet societal transport needs while minimizing their environmental impact. Several recent innovations also demonstrated potential benefits in global crisis scenarios. A review of the literature highlights five notable examples of such advancements (Table 14).

Table 14. The role of recent advances in public transport during potential global crises.

Solution	Role in Case of Potential Crises
Autonomous buses	• Lack of expenses for operators to employ drivers and the possibility of reducing transportation costs (economic crisis) • Reducing greenhouse gas emissions and lower carbon footprint (environmental crisis and health crisis) • Possibility of using it for contactless transport of infected people, samples, and tests (health crisis) • Higher energy efficiency and profitability of transport during sudden fluctuations in demand (health crisis)
On-demand public transport	• Possibility to generate savings by flexibly adjusting courses, shortening travel times, and increasing vehicle occupancy (economic crisis) • Reducing harmful gas emissions per passenger (environmental crisis and health crisis) • Increasing the resilience of the public transport system to potential sudden changes in demand for passenger transport (health crisis)

Table 14. *Cont.*

Solution	Role in Case of Potential Crises
In-vehicle air quality monitoring systems	• Lowering the costs of running transportation operations—less fuel or energy consumption (economic crisis) • Reduction of fuel or electricity consumption (environmental crisis and health crisis) • Increasing passenger safety through the ability to monitor air quality and reduce the spread of viruses (health crisis)
Contactless payment systems	• Lower costs related to the production, distribution, and storage of tickets, and no need to engage employees to conduct sales (economic crisis) • Increased demand for public transport travel due to speed and convenience of payment—decrease in use of private vehicles (economic crisis and environmental crisis) • Higher sanitary safety of travelers by eliminating contact with staff, touching cash, and using ticket machines (health crisis)
Smart stops and stations	• Increase overall transportation efficiency and improve comfort for users (economic crisis) • Support in terms of accessibility for different user groups (economic crisis and social crisis) • Reducing greenhouse gas emissions and improving air quality through integration with other innovative solutions (environmental crisis and health crisis)

Autonomous Buses

Autonomous buses are designed to operate independently, relying on advanced technologies, such as sensors, cameras, radars, and artificial intelligence (AI), to navigate and transport passengers safely. As part of the broader category of autonomous vehicles (AVs), these buses are usually electric, fostering a shift toward more sustainable and efficient public transport [278]. One major advantage of autonomous buses is the cost savings from eliminating driver wages. These savings can benefit both transit operators and passengers, potentially lowering ticket prices—an especially valuable aspect in the face of economic challenges and the need for resilience during global crises [279,280]. Autonomous buses also contribute to lower greenhouse gas emissions by optimizing driving patterns, such as braking and acceleration, and utilizing electric powertrains [281], which are more environmentally friendly. This shift could help combat climate change by reducing the carbon footprint of public transport systems [282,283]. In the context of epidemic risks, autonomous buses offer further advantages. They can transport infected patients to healthcare facilities with minimized human interaction or deliver samples and test kits to laboratories [45]. Research also supports the use of autonomous shuttles during fluctuations in passenger demand, highlighting their superior energy efficiency and cost-effectiveness under stringent health and safety protocols [284].

On-Demand Public Transport

On-demand public transport is a flexible transit system that adjusts to individual passenger needs in real time. Unlike traditional transport options, such as buses or trams, which operate on fixed schedules, on-demand services respond dynamically to user requests submitted through mobile apps or booking systems [46]. Research underscores the economic benefits of this approach for transport operators. With the flexibility to adjust to fluctuating demand, service providers can achieve cost savings by optimizing routes and schedules while reducing empty vehicle trips. However, on-demand public transport is noted to be especially beneficial in smaller urban areas, where demand can be more unpredictable [285,286]. Studies on bus transit have shown that on-demand systems reduced average travel times by 30% over a weekly cycle. Additionally, vehicle occupancy rates increased from 8% to over 50%, and emissions per passenger dropped by over 70% compared to traditional scheduled buses [47]. These findings highlight the alignment of on-demand transport with sustainable transport objectives. Other studies highlight the effectiveness of the on-demand system in response to epidemic threats, as evidenced during the COVID-19 pandemic [287]. The primary benefit was the enhanced resilience of the public transport system to disruptions, enabled by the system's flexible adaptation to varying threat levels and mobility restrictions [146,288].

In-Vehicle Air Quality Monitoring Systems

In-vehicle air quality monitoring systems are sophisticated technologies that enable real-time monitoring and assessment of air quality within the vehicle cabin. Equipped with sensors to measure carbon dioxide, oxygen levels, and other compounds, as well as monitoring humidity and temperature, these systems provide vital information to drivers and passengers, helping reduce health and safety risks associated with extended time in enclosed spaces [289,290]. Air quality monitoring systems can enhance vehicle energy efficiency by adjusting HVAC functions based on current cabin air quality. This helps to lower fuel consumption and, most importantly, energy usage in electric and hybrid vehicles, reducing overall operational costs for transport providers [291]. Research also highlights the importance of this solution for advancing sustainable transport. By managing cabin air quality—particularly in electric vehicles—emissions are reduced both inside and outside the vehicle. This minimizes the need for frequent external air circulation, which in turn helps reduce energy consumption [292]. Most research emphasizes the impact of in-vehicle air quality monitoring systems on passenger health, particularly during health crises, such as pandemics [293,294]. These systems enhance passenger safety by actively monitoring and controlling harmful substances within vehicle cabins. As a result, they help reduce the spread of airborne pathogens, making public transport safer [295,296].

Contactless Payment Systems

Contactless payments in public transport allow passengers to pay for rides using a smart card, mobile device, or contactless bank card, eliminating the need for cash or ticket machines. This method leverages near-field communication (NFC) technology, enabling transactions by simply tapping a card or device on a reader. Another option is digital payment through a mobile app, allowing for a seamless, fully digital transaction [297]. Contactless payments provide numerous benefits for both public transport operators and passengers. By removing the need for paper tickets and cash, transport operators reduce costs associated with ticket production, distribution, and storage. Additionally, automating payment processes minimizes the need for ticketing staff, yielding further savings. For passengers, contactless payments offer speed and convenience, shortening wait times at stops, accelerating boarding, and removing the need to carry cash or physical tickets. This convenient system encourages greater public transport use, potentially boosting revenues and decreasing reliance on private vehicles [298,299]. This shift has a positive impact on urban air quality by reducing greenhouse gas emissions from transport. Research also highlights the role of contactless payments in promoting public health, particularly during epidemics [300]. The COVID-19 pandemic underscored the importance of contactless payments as a crucial element in enhancing sanitary safety for travelers. This solution eliminated the need for contact with staff [301], cash handling, and using ticket machines, thereby reducing the risk of virus transmission [293,302].

Smart Stops and Stations

Smart stops and stations are innovative public transport solutions that leverage information and communication technologies (ICTs) to improve travel comfort and safety. Equipped with interactive displays showing schedules, mobile payment options, monitoring systems, and traffic management, these stops provide passengers with better access to information and services, enhancing the quality and safety of public transport [48,49].

Beyond economic benefits, smart stops and stations are also environmentally friendly. They provide real-time traffic information, boosting transport efficiency and passenger comfort by allowing for better travel planning, with updates on possible schedule disruptions [303]. A key advantage of smart stops and stations is their accessibility, as the infrastructure and informational interfaces can be customized to meet the needs of diverse user groups, including the elderly, disabled individuals, and immigrants. By eliminating barriers, these features can drive higher demand for public transport across all demographics [304]. Research emphasizes the environmental aspect of designing smart stops and stations. Studies advocate for solutions such as smart lighting management and photovoltaic panel installations, with additional support from the public power grid [305]. These innovations, especially when aligned with smart city concepts [49], can significantly reduce energy usage, lower local CO_2 emissions, and contribute to better air quality.

5. Conclusions

5.1. General Summary

The modern world remains exposed to a range of threats, which, as recent decades have shown, can lead to severe consequences and global crises. Additionally, ongoing environmental degradation and disruptions to the climate system exacerbate these problems, causing negative impacts on human health, the economy, and society. The goal of this publication, which was to identify the latest solutions in sustainable transport development and to highlight their relevance in the context of potential global crises, has been achieved. The results not only identified solutions crucial for the stability of the economy and transport sector in crisis situations but also suggested future research directions in this area. Moreover, these findings can serve as a resource for policymakers and transport organizers in implementing actionable recommendations.

5.2. Practical and Theoretical Contributions

This study offers a valuable practical contribution by presenting a series of transport solutions that, while aligned with the principles of sustainable development, primarily aim to enhance transport resilience to potential global crises. The results presented in the paper contribute to the sustainable development of transport by identifying the latest technological solutions that can reduce greenhouse gas emissions, promote energy efficiency, and improve safety and increase the overall stability of the transport sector. Innovations such as alternative drives, autonomous vehicles, and intelligent traffic management systems can significantly reduce the carbon footprint and ensure the continuity of transport services even during crises, such as financial breakdowns, epidemics, or armed conflicts, while reducing dependence on fossil fuels and increasing the reliability of logistics. Emission monitoring systems allow improved air quality, which is important in health crises, such as the COVID-19 pandemic. Autonomous technologies, such as unmanned vehicles and drones, can support logistics during crises, delivering medicines or other resources to dangerous or isolated regions. It is also worth pointing out the benefits of this study for future vehicles. The results showed that means of transport, such as AVs, alternatively powered vehicles, or modular vehicles, consistently developed toward compatibility with intelligent transport systems, can optimize traffic, reduce energy consumption and harmful emissions, and become more integrated with the infrastructure. Moreover, vehicles could benefit from the expansion of charging infrastructure, including stations using renewable energy. As a result, this would reduce the dependence on traditional fuels and the negative impact of transport on the environment. The article provides a practical foundation for decision-makers and transport organizers, offering recommendations on which solutions can be implemented to make the transport sector more resilient and environmentally friendly. Possible future actions can include testing and popularizing intelligent fleet management, expanding green infrastructure, and continuing work on integrating V2X-related technologies. A further step could be the implementation of autonomous solutions and the popularization of modular vehicles, which is justified due to their ease of adaptation to changing crisis conditions and increased resilience of transport systems.

The theoretical contribution of this study includes definitions, examples, and classifications of modern transport solutions, as well as the characterization of global crises. The concept of sustainable transport development was also discussed in detail, including the principles that should be met. The literature review allowed for the identification and categorization of specific transport solutions into categories, such as powertrain technologies, intelligent transport systems (ITS), logistics and delivery innovations, integration of transport systems, infrastructure development, modern vehicle solutions, and advances in public transport. This publication also provided a characterization of recent global crises and a classification that included economic, health, environmental, social, and military crises. As a result, this approach established a theoretical foundation that facilitates an understanding of the application of specific transport solutions in the face of potential global crises and underscores their importance for sustainable transport development.

5.3. Limitations and Further Research

This study faces several limitations that may affect its findings. First, the source selection was restricted by publication date. Since the review focused on recent research advances, only literature published from 2020 onwards was considered. This choice may have overlooked older, yet still valuable, studies on sustainable transport solutions relevant to potential crises. Another limitation is that the review drew exclusively from available scientific publications. Consequently, the findings may not fully capture the real-world challenges of implementing the proposed innovations, potentially overlooking obstacles, such as societal resistance to new technologies. There are also limitations related to source selectivity, as the review was based on research from only four scientific databases. This approach may have excluded other significant studies in less widely used databases or articles not indexed in these databases. Therefore, the review may not present a complete picture of the current state of knowledge on the topic.

This study also indicated possible directions for future research in sustainable transport solutions, which are also relevant in the context of possible crises. Given the results obtained, empirical studies on the effectiveness of implementing individual innovations based on geographical location and social diversity would be appropriate. These analyses could examine cost–benefit assessments, environmental impact, and societal acceptance of these solutions. Another critical area for future research involves developing hypothetical scenarios to prepare the transport sector for various crises and associated disruptions. The literature review also highlighted the importance of advancing research on the integration of autonomous technologies with urban infrastructure due to their potential to reduce emissions and improve energy efficiency. Finally, investigating the impact of international cooperation on transport technology development would be beneficial, particularly regarding access to renewable energy sources, legal regulations, and potential trade barriers.

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Article

Analysis of the Relationship Between Energy Consumption in Transport, Carbon Dioxide Emissions and State Revenues: The Case of Poland

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Abstract: The observed increase in demand for transport leads to higher energy consumption, which still predominantly originates from fossil fuels. As a result, the transport sector remains one of the main sources of GHG emissions. At the same time, transport activities bring economic benefits by generating public income and contributing to GDP. This article analyzes the relationship between total final energy consumption in transport, CO_2 emissions from transport, and government revenues, using Poland as a case study. The study applies Johansen's cointegration method to identify long-term relationships between time series. Unlike many cross-country studies, this research addresses a gap by focusing specifically on Poland—a post-transition economy where the transport sector holds both fiscal and environmental significance. After cointegration test, the Impulse Response Function was used to examine dynamics and identify system shocks. Results indicate that energy consumption in transport significantly affects both CO_2 emissions and government revenues. A rise in energy use leads to higher emissions and also correlates with increased public income. The study contributes to the understanding of how transport-related energy use impacts both fiscal outcomes and emissions in a national context. These findings offer a foundation for shaping future policies that promote economic growth and stable revenue while encouraging more efficient energy use and lower emissions.

Keywords: energy use; CO_2 emissions; government revenue; transportation; Poland; Vector Autoregressive Model; Vector Error Correction Model; Johansen's cointegration approach

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1. Introduction

Currently, a well-functioning transport sector is a fundamental driver of economic development in many countries, ensuring not only the movement of goods and passengers but also serving as a crucial component of the national energy system and financial policy [1,2]. The increasing demand for transport, driven by urbanization, globalization, and rising living standards, leads to intensified energy consumption, which still largely relies on high-emission fossil fuels [3,4]. This dominance makes the transport sector one of the main sources of greenhouse gas (GHG) emissions, including carbon dioxide (CO_2) [5], which, when released in excessive amounts, contributes to undesirable climate changes [6]. On the other hand, transport activities bring significant economic benefits, not only by generating financial resources through instruments such as excise duties and taxes but also by contributing to gross domestic product (GDP) through its close links with other economic sectors. Therefore, government policies must aim for an economic and environmental balance, ensuring stable budget revenues while simultaneously implementing mechanisms to mitigate environmental degradation [7]. This poses a challenge primarily for governments but also for policymakers and other entities responsible for shaping the economy, organizing transport, and protecting nature. The scientific community has also been consistently conducting research in this area, dedicating numerous studies to these issues.

There are many studies focused on emissions and energy consumption in transport [8,9]. Particular attention is given to the high level of emissions in road transport. An analysis of CO_2 emissions convergence from road transport in a sample of 22 European countries between 1990 and 2014 showed that these emissions tended to equalize, with the pace of this process depending on specific structural factors. Over the years, the dynamics of emission level equalization have intensified, leading to a situation where countries with lower emissions have gradually caught up with those that were previously at the forefront of pollution [10].

Given these results, the European Union's climate goals of significantly reducing emissions in Europe by 2050 are gaining increasing importance. It is emphasized that achieving this objective requires a combined approach, including fleet electrification and an energy policy that prevents the transfer of transport emissions to other sectors [11]. Another study examined possible scenarios using Italy as a case study, estimating the demand for road transport in Italy (for the years 2005, 2019, 2022, and 2030) and assessing greenhouse gas emissions. The findings showed that even under optimistic assumptions, GHG emissions could only be reduced by 33%, which is still far below the target [12]. Therefore, to meet such ambitious reduction goals, continuous monitoring and the implementation of new strategies are necessary. However, the impact of these measures varies depending on a country's level of economic development and transport structure [13]. In Europe, in recent years, significant progress has been made in fuel efficiency and vehicle propulsion technologies [14]. There is also potential in the digitalization of passenger transport, where technologies like Mobility-as-a-Service (MaaS) can enhance mobility while simultaneously reducing fuel consumption and air pollution [15].

The literature also highlights that fiscal policies can influence both energy consumption and carbon dioxide emissions, thereby contributing to environmental protection [16]. A study analyzing public attitudes toward changes in fossil fuel taxation in 23 European countries considered the level of political trust. The results indicated that while most Europeans (78%) believe in anthropogenic climate change and its associated risks, only 33% of respondents support tax increases [17]. Overall, changes in fuel tax systems show that raising fees often leads not only to a short-term decline in fuel consumption but also to higher tax revenue. Furthermore, it is emphasized that such additional revenues could significantly contribute to financing public transportation and developing environmentally friendly infrastructure [18]. On the other hand, it is pointed out that tax increases, despite generating higher revenues in the initial phases, may, in the long run, lead to economic deterioration, particularly in countries heavily reliant on the transport sector [19]. Another noteworthy type of government intervention involves tax incentives and subsidies for the purchase of electric vehicles, aimed at encouraging consumers to choose more environmentally friendly forms of transport. These measures are considered tools that help balance public spending with increasingly strict energy consumption and emissions requirements [20].

Publications are increasingly analyzing the impact of legislative measures related to emission reductions on national economies and the functioning of the transport sector. A key area of focus is carbon taxes imposed on fossil fuels, which are proportional to the greenhouse gas emissions generated during combustion [21]. One particularly notable case is the Carbon Border Adjustment Mechanism (CBAM), a tool designed to level the playing field and reduce "carbon leakage" outside the EU. It does so by applying import taxes (and/or export subsidies) based on the carbon content of products from countries with varying levels of climate policy stringency [22]. Another strategy analyzed by researchers is the European Union Emissions Trading System (EU ETS), which aims to gradually reduce GHG emissions in key economic sectors through the allocation and trading of CO_2 emission allowances [23]. Additionally, it is worth mentioning the continuously tightening EURO standards, which define permissible emission levels for vehicles. These regulations have led to the introduction of more environmentally friendly vehicles on European roads, improving air quality and, consequently, public health [24]. All these instruments contribute to reducing CO_2 emissions, but they may also have varied effects on the socio-economic conditions of a country. Research suggests that well-implemented climate, technological, and fiscal policies can not only effectively reduce emissions but also ensure the economic stability of a country [25–27].

A review of the literature also reveals that authors frequently use mathematical modeling to examine the relationships between energy consumption, emissions, and national economies. For example, the decoupling method has been applied to assess the relationship between transport-related GHG emissions and economic growth in EU countries [28]. Meanwhile, the Granger causality test has been used to analyze the relationship between energy consumption and economic growth in the ASEAN-5 countries, which include Indonesia, Malaysia, Thailand, Singapore, and the Philippines [29]. A broader approach, the Vector Error Correction Model (VECM), has been applied to evaluate the relationships between freight transport, energy consumption, economic growth, and greenhouse gas emissions in Tunisia [30]. Additionally, Johansen's cointegration method has been used to determine causal relationships between transport infrastructure, energy consumption in transport, and economic growth [31]. Furthermore, an analogous procedure, extended with a wavelet-based likelihood ratio test, has been used to examine the long-term relationship between CO_2 emissions and real GDP in G7 countries [32].

However, less attention in the literature has been given to studying long-term relationships between energy use in transport, harmful gas emissions, and the budget revenues of the Polish state, despite the potential for analysis using appropriate statistical methods [33]. This issue is particularly relevant in the context of the Polish economy, where the transport sector plays a dual role. The relationship between government revenues and energy consumption in the transport sector is based on two-way mechanisms, well documented in the economic literature. First, fiscal policy has a direct impact on the decisions of economic entities and consumers through instruments such as excise tax on fuels, VAT, registration fees, or subsidies for low-emission means of transport. As the authors note, e.g., in [34,35], energy taxes not only play an income-generating role, but are also an effective tool for reducing negative externalities, such as pollutant emissions. It is also worth emphasizing that there is a return effect. The level of energy consumption, including transport fuels, generates revenues for the state budget, which is an important component of fiscal revenues. In countries such as Poland, where a significant part of revenues from excise tax and VAT comes from the road transport sector, variability in fuel consumption may translate into fluctuations in budget revenues.

Moreover, in the context of transition countries, fiscal policy is playing an increasingly important role in shaping the direction of modernization of the transport and energy sectors, for example through a system of tax incentives, subsidies and fiscal preferences for specific types of vehicles or technologies. As indicated by studies [36,37], such a "green fiscal transformation" can serve both environmental and budgetary purposes.

The above relationships suggest that there may be long-term relationships between fiscal revenues and energy consumption in transport, which justify the use of cointegration analysis tools. Although this study does not introduce a fully formalized theoretical model, it is based on the paradigm of mutual feedback between fiscal policy and energy decisions (so-called policy feedback loop [38]), which provides the basis for the hypothesis of the existence of a structural relationship between the variables studied.

In the empirical model, this feedback mechanism is captured through a fiscal revenue variable that reflects overall central government income, including tax revenues from energy consumption in transport. While this variable is used in aggregated form, it remains analytically meaningful in the Polish context, where revenues such as excise duties and VAT on transport fuels represent a structurally important and relatively stable component of public finances. The use of this variable reflects the functional link between transport energy consumption and budget revenues, and allows for tracing long-term interactions within the model framework.

However, while previous studies have examined similar links in broader regional or global contexts, relatively little attention has been paid to country-specific dynamics, especially in economies like Poland. As a post-transition country, Poland represents a combination of structural and institutional features that are rarely analyzed together. These include the still-important role of coal in the energy mix, the asymmetric fiscal response to price shocks in the energy sector, and the dynamic but fragmented changes in transport policy. However, in most existing studies Poland is treated as one of many points in panel or multi-country analyses, which causes specific country-level mechanisms to be aggregated or overlooked. This is why studies focusing exclusively on this country remain relevant. The study proposed in this article focuses not only on the application of the Johansen method, but also on the deliberate adjustment of the variable set to reflect the specific institutional configuration of fiscal intervention in the Polish energy sector, including environmental taxes and subsidies, which are applied differently than in Western European countries. While the method itself is not novel, its application in this particular setting is informed by the policy feedback framework, which highlights how fiscal instruments (such as fuel taxation) not only influence energy consumption and emissions, but are also shaped by them over time. This bidirectional relationship, especially visible in Poland, where a significant share of public revenue depends on fossil fuel consumption, creates a context-specific dynamic that cannot be fully captured in cross-country studies assuming more harmonized fiscal or environmental systems. Although the model used in the study does not introduce a new formal architecture, its application in the context of Poland allows for identifying long-term structural patterns between energy use, emissions, and government revenues that remain underexplored in the existing literature. In this way, the study contributes to the empirical understanding of fiscal–energy interactions in post-transition settings and may serve as a reference point for future comparative research. This research gap has therefore become the focus of this article.

The aim of this publication was to analyze the relationship between total final energy consumption in transport, carbon dioxide emissions from transport, and government revenues, using Poland as a case study. This study is based on two key research questions:

- What are the relationships between total final energy consumption in transport, CO_2 emissions from transport, and government revenues?
- What is the direction and nature of the long-term dependencies between the analyzed time series variables according to Johansen's cointegration method?

In response to these questions, the article first presents the research background by characterizing the transport sector in Poland in terms of energy consumption, carbon dioxide emissions, and the country's economic condition. Subsequently, the core analysis of the relationships between these variables is conducted. The study begins with an assessment of the stationarity of the examined time series. Next, Johansen's method is applied, utilizing the Trace and Max-Eigenvalue test statistics. Once the cointegrating relationships within the analyzed time series are established, the Impulse Response Function (IRF) is calculated to gain a deeper understanding of both the short- and long-term dynamics between the variables, as well as to identify the main transmission channels (shocks in the system). The results primarily confirm the presence of long-term relationships between key variables for the transport sector, environmental sustainability, and the national economy. This is particularly important for shaping future state policies, which should aim to foster economic growth and, consequently, increase government revenues, while simultaneously optimizing energy consumption and reducing greenhouse gas emissions associated with rising transport demand. The study also has practical implications for the development of sustainable transport strategies (e.g., promoting electromobility and public transport) and for tax law reforms, ensuring stable budget revenues while limiting the use of high-emission energy sources in transport. Additionally, knowledge about shocks in the relationships between the analyzed time series can serve as a foundation for more informed energy management in the transport sector during crisis situations, such as sudden fuel price increases or the introduction of new, stringent climate regulations.

The article is structured into several sections. The study begins with an introduction to the research topic and a review of the current state of the literature related to the examined field. This section also outlines the research objective and its significance, as well as formulates the research questions. Next, a characterization of the transport sector in Poland is provided, focusing on total energy consumption, CO_2 emissions, and its connection to the country's economic condition. Chapter three presents the materials used in the study and describes the application of Johansen's cointegration method along with complementary analytical tools. In the following section, chapter four, the obtained results are presented and discussed. Finally, the study concludes with a general summary, formulation of key findings, discussion of limitations, and potential directions for further research.

2. The Transport Sector in Poland in Terms of Energy Use, Emissions, and Economic Condition

Poland is a country located in Central Europe, serving as a bridge between the eastern and western parts of the continent. It is a key transit hub where major transportation routes intersect, connecting regions with diverse environmental and economic conditions. As a result, Poland ranks among the most significant transit countries in Europe. Its strategic position is further reinforced by the fact that Poland's eastern border also serves as the external border of the European Union, making it a crucial strategic and trade partner for the entire region [39]. Passenger and freight transport play a fundamental role in the economy and society, and as Poland continues to develop ongoing changes in the transport sector are observed. In this regard, legislative initiatives aimed at making transport more efficient, environmentally friendly, and safe are particularly noteworthy [40,41]. Efforts are being made to meet transport demand while simultaneously minimizing negative environmental impacts, aligning with the principles of sustainable development [42]. Another key factor driving the growing importance of transport in Poland is government budget expenditures on expanding the vehicle fleet, developing infrastructure, and enhancing the transport network. This is clearly reflected in the National Road Construction Program for 2014–2023 (with a perspective until 2025), which aims to build 3767.9 km of roads with a total budget of approximately 163.9 billion PLN.

The program includes the construction of 324.2 km of motorways, 2948.9 km of expressways, and 43 bypasses with a total length of 447.2 km [43]. Over the years, these developments have allowed citizens to travel more safely and comfortably, while ensuring that goods reach their destinations faster and without disruptions in supply chains. Expanding on this, the growing importance of modern transport solutions, including logistics process automation [44] and intelligent traffic management systems [45], is becoming increasingly evident. Innovative and environmentally friendly transport solutions, such as vehicles powered by alternative energy sources, including electricity, hydrogen or biofuels, as well as advanced emission reduction technologies, are playing an increasingly important role across the sector [46–48]. All these transformations are a response to contemporary economic and environmental challenges, stemming from the dependence of national development on the transport sector. Since transport serves as a critical link for multiple economic sectors, it also generates significant revenue for the state budget, primarily through fuel excise taxes, road tolls, and other transport-related taxes. Thus, economic growth and the expansion of the transport sector directly influence budget revenues. However, while transport acts as a driver of growth, it is also one of the largest consumers of energy and a major source of greenhouse gas (GHG) emissions [49,50]. The development of road infrastructure, the increasing number of vehicles, and the intensification of trade in recent decades have led to a systematic rise in energy demand within the transport sector. In Poland, transport has become the largest consumer of final energy, meaning the energy delivered to end users that excludes energy consumed by the energy sector itself [51]. After 1998, the transport sector overtook industry in energy consumption, as industrial energy use stabilized over the past few decades. Since 2018, transport has also surpassed the energy consumption of Polish households. In 2019, total transport energy consumption reached 952.6 PJ. Due to the COVID-19 crisis in 2020, it dropped to 910.5 PJ. By 2022, it had surged to a record-high 999.5 PJ [52]. These trends highlight the critical role of transport in Poland's economy and financial stability while also pointing to challenges, particularly in terms of energy security and GHG emissions. Poland's total energy consumption by sector from 1990 to 2022 is shown in Figure 1.

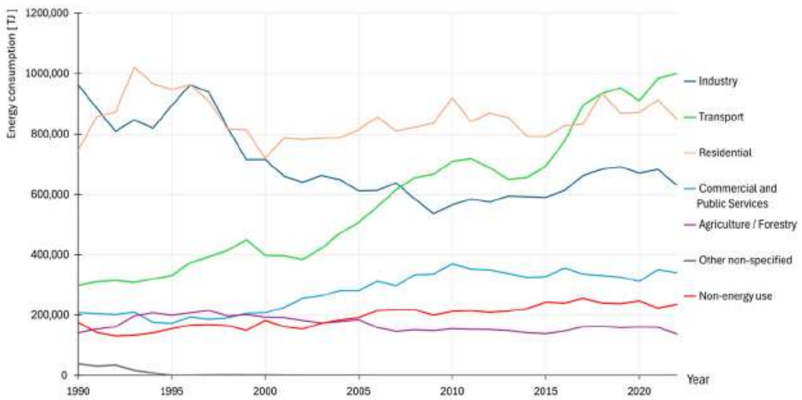

Figure 1. Total final energy consumption by sector in Poland.

Despite the numerous efforts mentioned earlier to improve energy efficiency and implement low-emission solutions, transport in Poland, as in many other European countries, remains heavily reliant on petroleum-based products. This is primarily the result of the significant role of road transport in the overall transportation movement, as well as the widespread use of internal combustion engines as power units [53,54]. Since the 1990s, there has been an increase in total energy consumption in transport, accompanied by the continued dominance of petroleum products. Such a situation has a negative impact on pollution levels and makes the sector particularly vulnerable to fluctuations in oil prices, which in turn affects other areas of life, directly impacting consumers [55,56]. Therefore, the transition towards alternative, more eco-friendly energy sources is crucial [57]. Until 1999, aside from petroleum products, electricity was the only other significant energy source used. The energy mix became more diverse after 2007, with a noticeable but gradual rise in the share of biofuels, waste, and natural gas, indicating some attempts to diversify energy sources. However, the scale of these changes remains limited, as confirmed by data for 2022, when energy consumption in transport from petroleum products amounted to 932,145 TJ, while consumption from all other sources totaled just 67,399 TJ (Figure 2) [52].

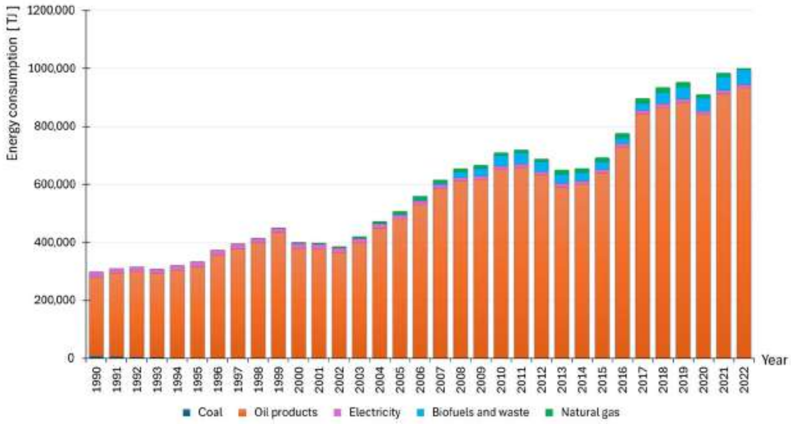

Figure 2. Total final energy consumption in the transport sector by source in Poland.

In the context of final energy consumption in Polish transport, it is also important to note how consumption has developed in relation to different subsectors over the last few years. Passenger transport has consistently shown the highest demand for energy, which is related to the high and still increasing number of vehicles on the roads, as well as the significant role of public transport within the entire system [58,59]. Recent, noticeable disruptions in passenger transport were caused by the market collapse following the outbreak of the COVID-19 pandemic. In 2020, there was a significant decrease in the number of passengers transported, resulting from restrictions on movement and reduced societal mobility [60], which in turn led to a drop in total energy consumption. In freight transport, energy use was lower compared to passenger transport, but it also increased over time. This sector exhibited greater stability in terms of responding to economic disruptions and the crisis caused by the pandemic. Moreover, when comparing energy consumption in freight transport with that of heavy-duty vehicles, it is noticeable that in recent years, there has been an increasing demand for this type of transport. This is a result of the growing demand for goods, including due to the rise of e-commerce services, which logistics [61] must accommodate. The total final energy consumption by subsectors in the years 2020–2022 is shown in Figure 3 [52].

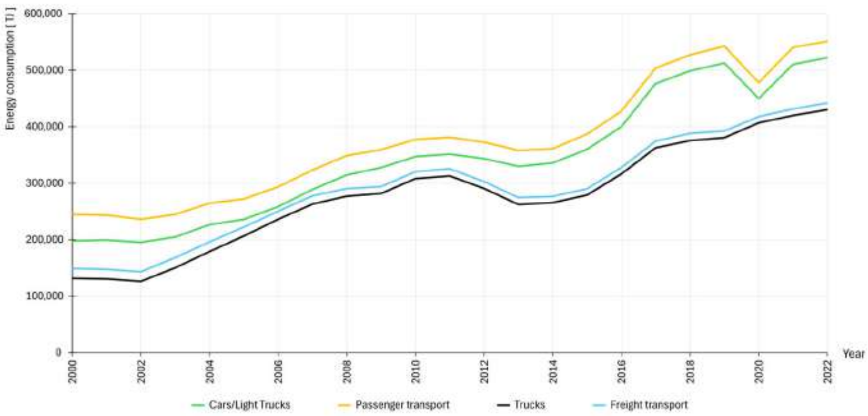

Figure 3. Total energy consumption in transport in Poland by subsector.

The increase in energy consumption, particularly from the combustion of fossil fuels, leads to higher greenhouse gas emissions, including carbon dioxide. CO_2 absorbs and retains infrared radiation, contributing to atmospheric temperature rise. When emitted excessively due to anthropogenic activities, it intensifies the greenhouse effect. In the long term, this is associated with a chain of catastrophic events, such as rising sea levels, changing climatic conditions, and altered precipitation patterns [62]. Additionally, fossil fuel combustion, which is the primary source of CO_2 emissions, also releases harmful substances, such as nitrogen oxides (NO_x) and particulate matter (PM) [63]. These pollutants degrade air quality and negatively impact human health [64]. However, a positive aspect is that, based on reports, Poland has observed a long-term downward trend in carbon oxide emissions. the most significant reduction occurred between 1990 and 2000. Despite this decline, coal remains the dominant source of CO_2 emissions, although its share in total emissions is gradually decreasing. The share of petroleum products and natural gas in CO_2 emissions has remained relatively stable over the past three decades. After 2005, there was a slight rise in emissions, likely due to the growing role of the transport sector. However, overall, fluctuations in emissions from these sources are minor, and their contribution to total emissions does not exhibit dynamic changes, unlike coal emissions. It is also important to consider data from 2019–2022, which show more noticeable fluctuations. These variations result from the COVID-19 pandemic, ongoing transitions in the energy and industrial sectors, and the increased energy demand following the crisis [65]. The CO_2 emissions by energy source in Poland between 1990 and 2022 are illustrated in Figure 4 [52].

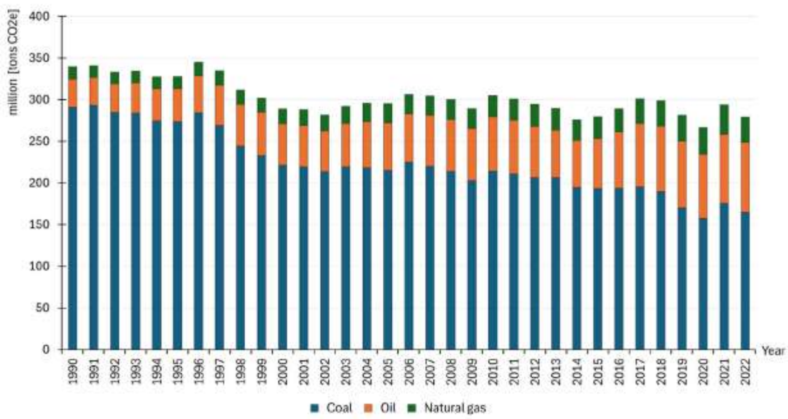

Figure 4. Carbon dioxide emissions by energy source in Poland.

The share of various energy sources in CO_2 emissions is reflected in the sectoral structure of these emissions. The largest source of CO_2 emissions between 1990 and 2022 was the electricity and heat production sector. However, it should be noted that this share has clearly declined year by year, mainly due to the development of green technologies, the implementation of more energy-efficient solutions, and government policies aimed at reducing heat losses and electricity consumption [66,67]. The industrial sector has also reduced emissions, albeit to a lesser extent than the energy sector. Meanwhile, emissions from the residential sector, as well as commercial and public services, have remained at a relatively similar level. Among the sectors analyzed, transport stands out with a continuous increase in emissions over the years, making it one of the few sectors that have not reduced their carbon footprint in the long term. Although economic disruptions and the COVID-19 pandemic caused temporary declines [68], the sector quickly returned to a growth trajectory. While total emissions from transport are significantly lower compared to other sectors—67.34 million tons of CO_2e in 2022 for transport, versus 140.26 million tons of CO_2e for electricity and heat production—the persistent upward trend is an undesirable phenomenon for the environment. This situation confirms that transport remains a challenge for climate policy, prompting numerous measures and strategies aimed at its decarbonization [69,70]. An example of such efforts is the European Union's regulations on CO_2 emissions from transport. According to the revised climate targets, between 2030 and 2034, CO_2 emissions from new passenger cars in EU countries must decrease by 55%, while emissions from new vans must be reduced by 50% compared to the target levels set for 2021. Additionally, the regulations stipulate that by 2035, all new urban buses must be zero-emission [71] by 2035. Carbon dioxide emissions by sector in Poland from 1990 to 2022 are shown in Figure 5 [52].

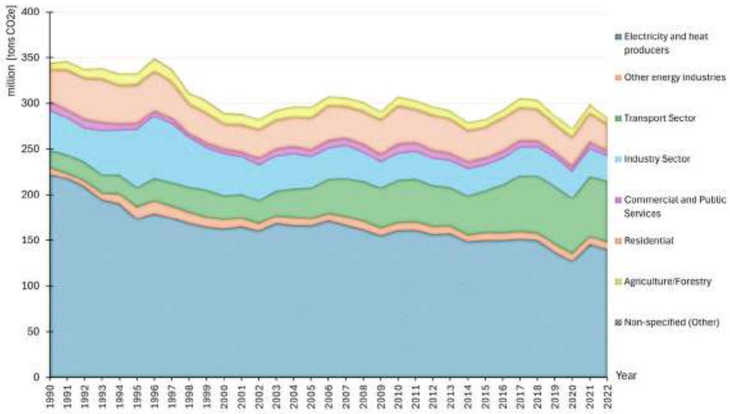

Figure 5. Carbon dioxide emissions by sector in Poland.

In the context of the discussed area, it is also essential to address the economic condition of Poland. The primary indicator reflecting the level of a country's development is Gross Domestic Product (GDP). This metric measures the total value of all goods and services produced within an economy over a specific period [72], which, in the case of transport, includes both the value of transport services and investments in infrastructure. The direct contribution of the transport sector to GDP is approximately 6%. However, its overall significance to the economy is much greater, as road transport plays a crucial role in the supply chain of sectors responsible for nearly half of Poland's GDP [73]. Gross Domestic Product is closely linked to budget revenues, which are financial resources accumulated in public funds. In the case of transport, these revenues include proceeds from fuel excise taxes, road tolls, and taxes on business activities conducted within the transport sector [74,75]. Between 1990 and 2022, a consistent increase in both GDP and budget revenues was observed, indicating that economic growth translated into higher state budget inflows. In this context, transport plays a crucial role—government investments in infrastructure expansion and the development of the communication network support GDP growth, while tax policies influence budget revenues, thereby generating funds for further expenditures. The relationship between these indicators demonstrates that economic growth leads to a stable expansion of public finances, which, in turn, positively affects transport activity, both in freight and passenger transportation. This correlation is illustrated in Figure 6, presenting a comparison of GDP and government revenues from 1990 to 2022 [76,77].

The characteristics of Poland in terms of final energy consumption in transport, CO_2 emissions from transport activities, and state budget revenues indicate a certain relationship between these factors. Conducting further analyses using appropriate statistical methods will not only help determine the exact dependencies between these time variables but also establish the direction and nature of their long-term relationships. These findings will be presented in the following sections of the publication.

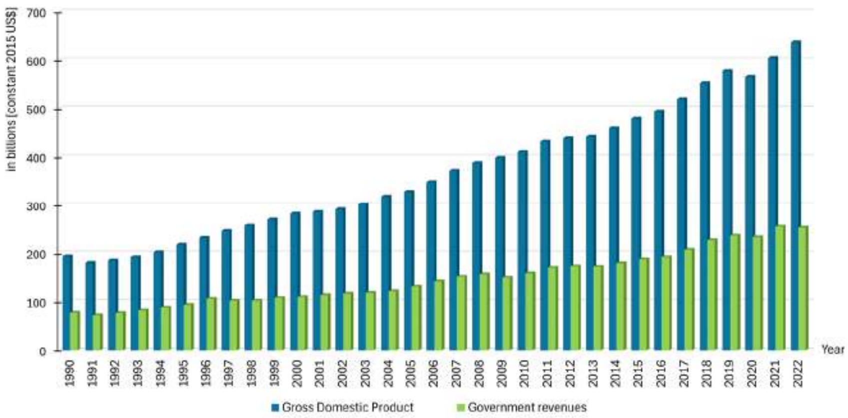

Figure 6. Comparison of gross domestic product in Poland with government revenues.

3. Materials and Methods

The article utilizes data for Poland concerning total final energy consumption in transport, carbon dioxide (CO_2) emissions from transport activities, and government revenues. The study covers the period from 1990 to 2022. Data were obtained from statistical reports by Statistics Poland (GUS) [78,79] and databases provided by the following organizations: International Energy Agency (IEA) [52], World Bank Group [77,80], and the International Monetary Fund (IMF) [76].

The considered variables were defined and expressed as follows:

- Total Final Energy Consumption in Transport (TFECT)—measured in terajoules [TJ], based on the data collection and conversion methodology of the IEA [81];
- Carbon Dioxide Emissions from Transport (CO_2T)—measured in million metric tons of carbon dioxide equivalent [Mt CO_2e], according to the World Bank approach utilizing the Emissions Database for Global Atmospheric Research (EDGAR) [82];
- Government Revenues (GREV)—expressed as a percentage of Gross Domestic Product in Poland [%GDP], based on the principles of data collection and calculations by the IMF [83]. This relative indicator enables improved comparability over time by reflecting fiscal performance relative to economic size [77].

To address potential distortions caused by currency fluctuations and inflation over the long study period, macroeconomic variables such as GDP were converted to constant 2015 U.S. dollars (USD), following the conversion methods used by the World Bank Group and the Organisation for Economic Co-operation and Development (OECD) [84]. Since GREV was expressed as a share of GDP, no further currency adjustment was required for this series. As a result, this provided a consistent and transparent basis for time series analysis.

As the variables are expressed in different units, care was taken to ensure that this dimensional heterogeneity does not bias the analysis. According to the established econometric literature [85,86] cointegration techniques are scale-invariant, provided all series are integrated of the same order. This condition was verified using three complementary tests of stationarity: the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests. In addition, numerical stability was examined through simulation-based diagnostics and impulse response analysis, which revealed no signs of model distortion or instability due to differences in measurement units.

To achieve the research objective, Johansen's cointegration test was applied. This statistical method is commonly used to analyze long-term relationships between multiple time series variables. It is frequently employed in economics and finance to examine whether stable, long-term relationships exist between non-stationary time series that may be cointegrated [87]. Cointegration refers to a situation where the variability of two or more time series is similar in the long run. Although individual series may be non-stationary, their linear combination is stationary, indicating a stable long-term equilibrium relationship between them. This means that cointegrated series do not drift apart over time, suggesting an existing connection between them [88]. In such cases, Johansen's cointegration test is applicable, allowing for the identification of multiple cointegration vectors and determining their number [33]. This test, which assesses the cointegration of multiple time series, is based on the vector error correction model (VECM). However, before applying it, it is necessary to establish the vector autoregression (VAR) model [89]. The general vector autoregressive model, in which each variable has a vector value and matrices are used as coefficients, takes the general form given by the equation:

$$x_t = \mu + A_1 x_{t-1} + A_2 x_{t-2} + \ldots + A_k x_{t-k} + u_t, \quad (1)$$

where:

μ—mean vector value of the time series;
x_t—represents the vector of time series;
A_i—autoregressive coefficient matrices;
u_t—error terms.

The next step after estimating the VAR model is to convert the VAR model into its cointegration form, transforming it into the vector error correction model (VECM):

$$\Delta x_t = \mu + A x_{t-1} + \Gamma_1 \Delta x_{t-1} + \cdots + \Gamma_k \Delta x_{t-k} + u_t, \quad (2)$$

where:

$\Delta x_t = x_t - x_{t-1}$—differential operator;
Γ_k—matrix for each differential delay.

The Johansen test examines the null hypothesis of no cointegration, which occurs when the matrix $A = 0$ [90]. The testing of the number of cointegrating relationships utilizes two statistics: the Trace test, which examines how many cointegrating vectors exist, and the Max-Eigenvalue test, which assesses whether the number of cointegrating vectors is exactly equal to a specified value [91,92].

The Trace test evaluates the number of K linear combinations in the given time series. The test statistic for this test employs the sum of the logarithms of the eigenvalues of the cointegration matrix and is defined as follows:

$$\lambda_{trace}(r) = -T\sum_{i=r+1}^{k} ln(1 - \hat{\lambda}_i), \quad (3)$$

where:

T—number of observations;
k—number of variables in the model;
$\hat{\lambda}_i$—i-th eigen value estimated from the cointegration matrix;
r—the number of cointegrating vectors (null hypothesis of the test).

The null hypothesis (H_0) assumes that the number of cointegrating relationships is r, meaning there are at most r cointegrating vectors, whereas the alternative hypothesis (H_1) assumes that the number of cointegrating relationships is greater than r, meaning there are more than cointegrating vectors. The test is conducted iteratively, checking successive values. If λ_{trace} exceeds the critical value, H_0 is rejected in favor of H_1. However, if λ_{trace} is smaller than the critical value, H_0 is not rejected—indicating that the number of cointegrating relationships is not greater than r [93,94].

Unlike the Trace test, the Max-Eigenvalue test examines the number of cointegrating relationships individually rather than cumulatively. It tests whether the number of cointegrating vectors is exactly r, by comparing the largest eigenvalue from the cointegration matrix. The test statistic is defined as:

$$\lambda_{max}(r, r+1) = -Tln\left(1 - -\hat{\lambda}_{\ r+i}\right) \quad (4)$$

where:

$\hat{\lambda}_{\ r+i}$ − (r + 1)—the largest Eigenvalue estimated from the cointegration matrix.

The null hypothesis (H_0) assumes that the number of cointegrating relations is exactly r, while the alternative hypothesis (H_1) assumes that the number of cointegrating relations is $r+1$—that is, there is exactly one additional cointegrating vector. If λ_{max} exceeds the critical value, H_0 is rejected in favor of H_1, so there are at least $r+1$ cointegrating vectors. If λ_{max} is less than the critical value, H_0 is not rejected, so the number of cointegrating relationships remains at r [95]. Eigenvalues are crucial as they measure the strength of the long-term equilibrium relationship. Larger eigenvalues indicate stronger cointegration relationships [33,96,97].

Additionally, after establishing the cointegration relationships, the IRF function was applied to assess the dynamics between the time series and identify shocks in the system.

Within the scope of this study, mathematical modeling was conducted using R Core software (version 4.4.2) [98], primarily with the "urca" package, which provides a set of cointegration tests for time series analysis [99].

4. Results and Discussion

The study began with a graphical representation of all the examined time series. The charts sequentially present the total final energy consumption in transport (TFECT) (Figure 7), carbon dioxide emissions from transport activity (CO_2T) (Figure 8), and government revenue (GREV) (Figure 9).

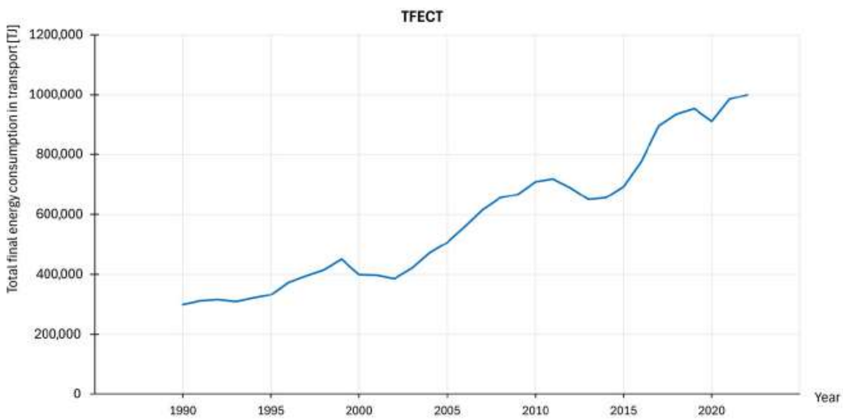

Figure 7. Total final energy consumption (TFECT) in Poland in the analyzed period.

Next, the stationarity of the time series of the analyzed variables was examined using the ADF (Augmented Dickey–Fuller test), PP (Phillips–Perron test), and KPSS (Kwiatkowski–Phillips–Schmidt–Shin test). For the variables to be included in further modeling, the time series they represent must be non-stationary in their raw form and stationary after first differencing. The results of the ADF test for time series derived from raw data are presented in Table 1, the PP test in Table 2, and the KPSS test in Table 3.

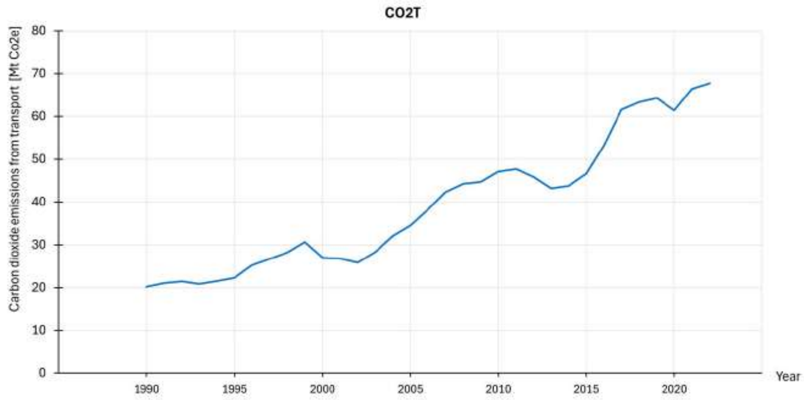

Figure 8. Carbon dioxide emissions from transport (CO_2T) in Poland in the analyzed period.

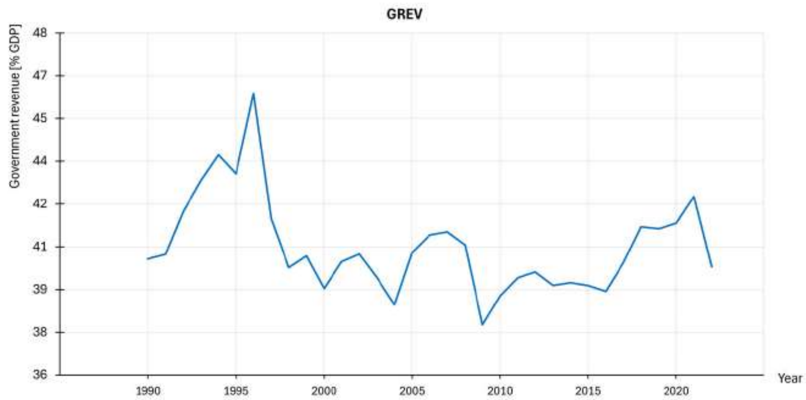

Figure 9. Government revenue (GREV) in Poland in the analyzed period.

Table 1. Dickey–Fuller test results for raw data.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	−1.658	0.705
CO_2T	−1.647	0.710
GREV	−2.587	0.346

Table 2. Phillips–Perron test results for raw data.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	−8.895	0.559
CO_2T	−8.982	0.554
GREV	−14.236	0.211

Table 3. Kwiatkowski–Phillips–Schmidt–Shin test results for raw data.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	0.889	0.01
CO_2T	0.887	0.01
GREV	0.883	0.01

The above results obtained using three different tests indicate that all the time series represented by the raw data are non-stationary. Therefore, in the next stage, the stationarity of the series after first differencing was examined. The results of the ADF test after first differencing are shown in Table 4, from the PP test in Table 5, and from the KPSS test in Table 6.

Table 4. Dickey–Fuller test results after first differentiation.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	−3.664	0.044
CO_2T	−3.733	0.038
GREV	−3.756	0.037

Table 5. Phillips–Perron test results after first differentiation.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	−22.630	0.013
CO_2T	−22.426	0.015
GREV	−34.312	0.001

Table 6. Kwiatkowski–Phillips–Schmidt–Shin test results after first differentiation.

Time Series (Variable)	Test Statistic	*p*-value
TFECT	0.140	0.1
CO_2T	0.138	0.1
GREV	0.067	0.1

Additionally, for each of the analyzed time series, a Monte Carlo simulation with 1000 replications was conducted to estimate the distribution of the Phillips–Perron (PP) test statistic under the null hypothesis of non-stationarity (random walk type process). First, simulations were performed for all time series derived from the raw data. The results are presented in Figures 10–13.

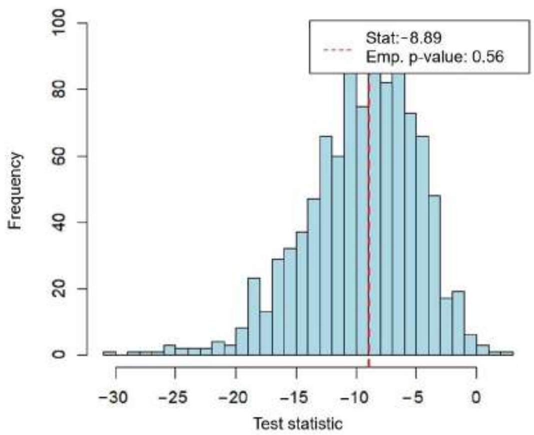

Figure 10. Monte Carlo simulation for PP test for TFECT variable (raw data).

Then, simulations were carried out for all analyzed time series after the first differentiation. The obtained results are shown in Figures 13–15, respectively.

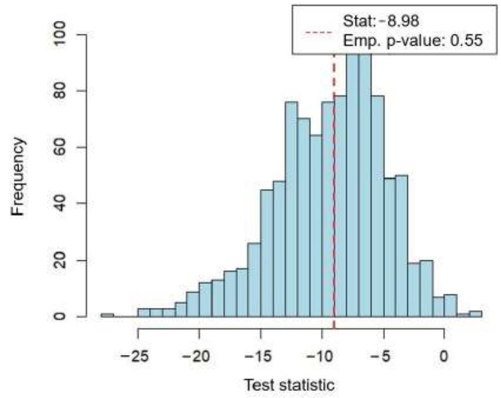

Figure 11. Monte Carlo simulation for PP test for CO_2T variable (raw data).

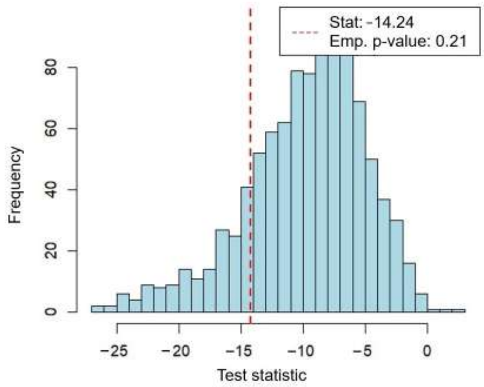

Figure 12. Monte Carlo simulation for PP test for GREV variable (raw data).

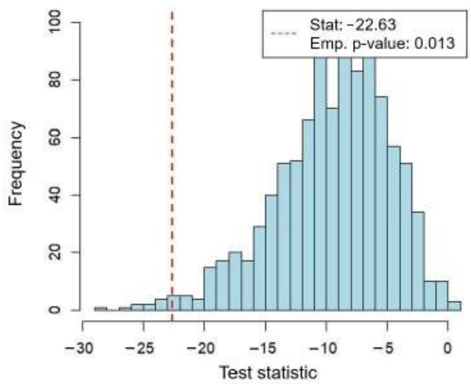

Figure 13. Monte Carlo simulation for PP test for TFECT variable (after first differentiation).

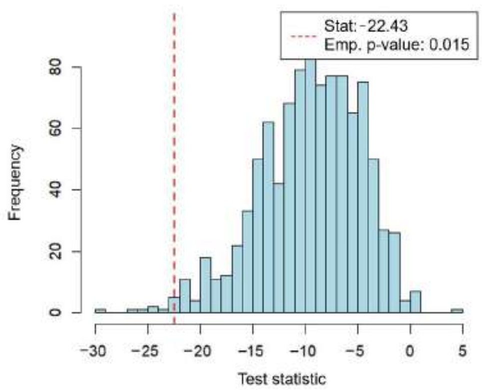

Figure 14. Monte Carlo simulation for PP test for CO_2T variable (after first differentiation).

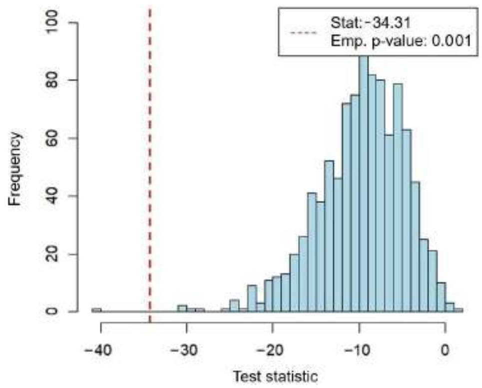

Figure 15. Monte Carlo simulation for PP test for GREV variable (after first differentiation).

The histograms (Figures 10–15) illustrate the distributions of the Phillips–Perron (PP) test statistic, indicating the positions of the actual test statistics as well as the corresponding *p*-values—both prior to and following the first differencing. This approach facilitates an evaluation of the strength of the evidence against the null hypothesis of non-stationarity. In the case of a non-stationary series (i.e., one for which the random walk hypothesis cannot be rejected), the observed PP test statistic is expected to lie near the center of the simulated distribution. The further the observed statistic is located in the left tail of the simulated distribution, the stronger the indication that the series is stationary. Accordingly, the results of the Monte Carlo simulations reveal that, for each of the analyzed time series after first differencing, the PP test statistic falls within the left tail of the simulated distribution, thereby providing substantial evidence in favor of stationarity.

To sum up, all obtained results confirm that considered time series represented by the raw data are non-stationary, whereas after first differencing, they exhibit stationarity. Therefore, it is possible to proceed with the Johansen cointegration test, starting first with the selection of the optimal lag order (Table 7).

Table 7. Selection of the optimal lag order for the Johansen test.

Criteria	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
AIC(n)	40.337	39.703	39.565	37.835	32.839
HQ(n)	40.608	40.190	40.268	38.754	33.975
SC(n)	41.312	41.458	42.100	41.150	36.935
FPE(n)	3.370×10^{17}	2.002×10^{17}	2.391×10^{17}	8.903×10^{16}	3.856×10^{15}

Given the obtained values, it can be observed that the optimal lag order is 5, and, therefore, this value was adopted for the subsequent part of the study. Next, the number of cointegration relationships was examined using two statistics—the Trace test and the Max-Eigenvalue test. The obtained results are presented below.

Eigenvalues (λ_i)

- 0.8877;
- 0.6988;
- 0.1823;
- 0.0268.

The results of the Trace test statistic (Table 8) indicate that the hypotheses for $r = 0$ and $r \leq 1$ should be rejected, but there is no reason to reject the hypothesis $r \leq 2$. Thus, it is assumed that there are two cointegrating vectors. The eigenvectors matrix (Table 9) presents the coefficient in each cointegration relationship. The first row of this matrix is normalized with respect to the TFECT time series, which serves as the normalizing variable.

This implies that each relationship is expressed relative to this series. High values for CO_2T and GREV suggest that these series play a significant role in the cointegration relationships. Therefore, cointegration includes TFECT, CO_2T, and GREV, forming linear combinations that remain stable over the long term.

Table 8. Values of Trace test statistic and critical values.

Cointegrating Vectors (r)	Test	10 pct	5 pct	1 pct
$r \leq 3$	0.76	6.50	8.18	11.65
$r \leq 2$	6.40	15.66	17.95	23.52
$r \leq 1$	39.99	28.71	31.52	37.22
$r \leq 0$	101.21	45.23	48.28	55.43

Table 9. Eigenvectors matrix—cointegration relations.

	TFECT.L5	CO_2T.L5	GREV.L5	PASS.L5
TFECT.L5	1.000	1.000	1.000	1.000
CO_2T.L5	-1.545×10^4	-1.669×10^4	-1.290×10^4	-1.366×10^4
GREV.L5	-1.771×10^3	8.413×10^3	-4.145×10^3	-2.389×10^2

Subsequently, the loading matrix (Table 10) was constructed. The analysis of this matrix reveals how each time series responds to deviations from long-term equilibrium. The largest absolute values occur for TFECT (≈1.61 and ≈2.28), indicating that this series reacts strongly to deviations from equilibrium in both cointegration relationships.

Table 10. Loading matrix of analyzed time series.

	TFECT.L5	CO_2T.L5	GREV.L5
TFECT.L5	1.614	2.280	−0.290
CO_2T.L5	1.009×10^4	1.910×10^{-4}	-1.524×10^{-5}
GREV.L5	3.459×10^4	-9.333×10^{-5}	1.617×10^{-5}

As demonstrated by the results presented above, the Johansen procedure confirmed the cointegration of the time series. Therefore, the next stage of the study involves estimating the VECM model. The estimated model includes the RLM (Restricted Linear Model) and the matrix of cointegrating vectors β, which accounts for long-term relationships between the time series. These are the linear combinations of the series that remain in equilibrium over the long run. In this analysis, two cointegration relationships and three time series are considered, meaning that the β matrix has dimensions 2×3. The values represented by this matrix indicate how the individual series are related to one another. High coefficients suggest strong dependencies between the series. The matrix of cointegrating vectors β including trend coefficients is shown in Table 11.

Table 11. Matrix of cointegrating vectors β with attached trend coefficients.

	ect1	ect2
TFECT.L5	1.000	6.776×10^{-21}
CO_2T.L5	0.000	1.000
GREV.L5	−34,483.640	−2.467
TREND.L5	−26,828.310	−1.807

In the first cointegration vector (ect1), TFECT.L5 is assigned a coefficient equal to 1, establishing it as the normalizing variable for interpreting the long-run equilibrium. The coefficient for CO_2T.L5 is 0, indicating that this series is not part of the first relationship. For GREV.L5, there is a large negative value, which suggests a strong inverse relationship with TFECT.L5. Additionally, the value of the trend coefficient suggests that there is a long-term trend affecting TFECT.L5. Based on the specified coefficients, the first cointegration relationship (ect1) can be expressed by the following equation:

$$TFECT.L5 - 34,483.64 \times GREV.L5 - 26,828.31 \times TREND.L5 = 0 \quad (5)$$

In the second relationship (ect2), CO_2T is the normalizing variable, which is why its coefficient is 1. For TFECT, the coefficient is 0 because this series is not part of the second relationship. The value of the coefficient for GREV.L5 indicates that as GREV.L5 increases, CO_2T.L5 decreases. Taking the values of the coefficients into account, the second cointegration relationship (ect2) can be expressed by the following equation:

$$CO_2T.L5 - 2.467 \times GREV.L5 - 1.807 \times TREND.L5 = 0 \quad (6)$$

In the next part of the study, after identifying the cointegrating relationships present in the considered time series, the Impulse Response Function (IRF) [100] was computed. IRF analysis allows for a deeper understanding of both short- and long-term dynamics between time series, as well as identifying the main transmission channels of shocks in the system. This analysis helps in determining how a change in one time series influences the dynamics of the entire system in subsequent periods. Particularly significant are sudden changes, or shocks. They primarily allow for assessing which time series are especially sensitive to changes occurring in others. Additionally, the IRF shows the direction of the influence—whether it is direct or opposite. Moreover, it reveals how long the shock effect lasts over time, i.e., whether the system quickly returns to equilibrium or if the shock causes long-lasting changes. The value of the IRF indicates the strength of the shock's impact. Large responses indicate a strong influence, while small ones show more subtle reactions [101,102]. The responses to shocks in the system were analyzed using all the considered time series. Figure 16 presents the impulse response from TFECT, while Table 12 shows the IRF values from TFECT in each period.

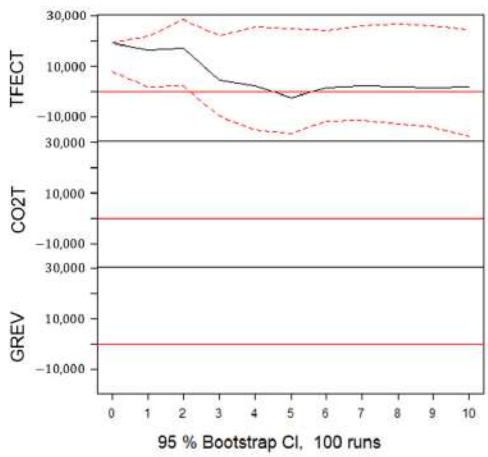

Figure 16. Impulse response from TFECT.

Table 12. TFECT's response to shocks in the system.

Period	TFECT	CO_2T	GREV
1	19,366.846	1.387	0.435
2	16,767.475	1.154	0.339
3	17,264.957	1.123	0.464
4	4907.827	0.269	0.117
5	2431.460	0.082	0.272
6	−2059.687	−0.144	−0.116
7	1617.437	0.147	0.063
8	2350.726	0.222	0.019
9	1967.259	0.184	0.126
10	1543.445	0.152	0.152
11	2185.142	0.182	0.210

A shock in TFECT leads to a notable rise in the first period (≈19,367), followed by a gradual decline over the next few periods. Around period 6, the effect turns slightly negative (≈−2060), after which the system settles at a new relatively stable level. This indicates a strong but short-lived reaction, with the system reaching a new equilibrium within a few periods. Regarding the shock in CO_2T, a small initial increase is observed (≈1.387 in period 1), but this effect quickly dissipates. Generally, there is little long-term impact—after several periods, the values are low. On the other hand, analyzing the shock in GREV, a very small effect is visible—a slight surge initially, which next diminishes with some fluctuations after third period.

The impulse response from TFECT shows an immediate and short-lived rise in CO_2 emissions. This is consistent with the dominant role of fossil fuels in the transport sector, where combustion leads to direct emission effects. GREV respond with a slight delay, reaching a peak in the third period (≈0.464). This lag does not result from the excise tax collection mechanism itself, but more likely reflects the time needed for increased fuel consumption to influence broader fiscal aggregates, including VAT and business-related taxes. These revenues often react indirectly or follow periodic reporting cycles. This pattern observed supports the presence of both immediate environmental effects and more gradual fiscal adjustments.

Next, the responses to shocks in the system with CO_2T were examined. The results are illustrated in Figure 17, and Table 13 presents the IRF values from CO_2T in each period.

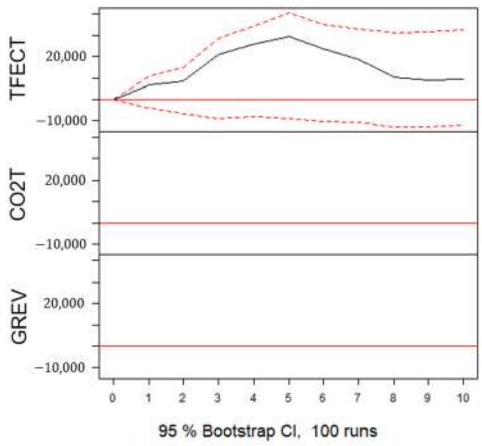

Figure 17. Impulse response from CO_2T.

Table 13. CO_2T response to shocks in the system.

Period	TFECT	CO_2T	GREV
1	0.000	0.175	0.374
2	6799.627	0.638	0.751
3	8591.020	0.733	0.414
4	20,978.393	1.543	0.460
5	25,905.726	1.842	0.488
6	29,414.847	2.060	0.522
7	23,882.844	1.657	0.442
8	18,964.084	1.243	0.590
9	10,317.802	0.652	0.371
10	8845.228	0.595	0.414
11	9529.344	0.698	0.357

Considering the shock in TFECT, CO_2T exhibits a pronounced rise, peaking at over 20,000 by period 4, before trending downward in subsequent periods. This indicates that while increased transport energy use has a strong effect on emissions, the influence diminishes progressively as the system adjusts. Analyzing the shock in CO_2T, a self-reinforcing effect is observed. CO_2 increases at first and gradually rises to its maximum level (≈2.06 after 6 periods), after which it starts to decline. Thus, it can be concluded that the shock in CO_2 emissions causes a lasting effect, which only fades after a longer period. Regarding the shock in GREV, an initial upward response (≈0.75 in period 2) is visible, but after a few periods, the effect is ambiguous. Therefore, state budget revenues may have some impact on CO_2 emissions, but this effect is not strong.

These results suggest that CO_2 emissions can reflect changes in transport-related activity that later translates into increased energy consumption. Rather than acting as a direct driver, emissions may indicate intensified use of transport services, including freight or passenger movement. The response of GREV, although limited in magnitude, points to a indirect linkage, where emissions-related activity contributes to fiscal inflows through fuel taxation or broader economic turnover. This interpretation shows differentiated responses in timing and scale across the transport-energy-fiscal nexus.

Similarly to previous analyses, the responses to shocks in the system with GREV were examined. The impulse response from GREV is shown in Figure 18, while Table 14 presents the IRF values from GREV in each period.

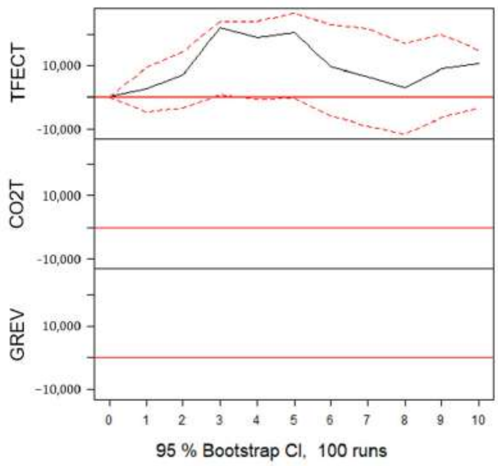

Figure 18. Impulse response from GREV.

Table 14. GREV's response to shocks in the system.

Period	TFECT	CO_2T	GREV
1	0.000	0.000	0.857
2	2591.472	0.274	0.407
3	7062.757	0.627	0.272
4	22,071.636	1.587	0.380
5	18,801.535	1.333	0.074
6	20,518.968	1.432	0.352
7	9682.863	0.649	0.340
8	6492.695	0.398	0.404
9	2817.795	0.192	0.186
10	8872.288	0.626	0.378
11	10,627.816	0.796	0.177

Taking into account the shock in TFECT, government revenues (GREV) rise sharply, exceeding 22,000 by period 4, and then gradually decline in the subsequent periods. This pattern highlights a direct fiscal response to increased transport energy use. Referring to the shock in CO_2T, GREV climbs more slowly, reaching approximately 1.43 in 6 period, and then experiences a downturn. This may result from cyclical changes in the domestic economy. Cyclical fluctuations are related to the degree of transport utilization, which in turn impacts carbon dioxide emissions from transport. However, these fluctuations do not cause significant disruptions in state revenue flows. When analyzing the shock in GREV, a preliminary surge in revenues (0.86 in the first period) is observed, but later oscillations occur, both upwards and downwards, which may indicate that the state's policy in this area is not sufficiently predictable, leading to varying effects on the long-term state of funds collected in public accounts.

The results obtained by the IRF function from GREV suggest that changes in fiscal capacity, even when variable, can indirectly influence energy consumption through policy channels such as infrastructure investment or demand stimulation. These effects are not immediate but may accumulate over time, especially in sectors that are energy-intensive by nature. The reaction of CO_2T is less consistent, which aligns with the fact that emissions are not directly shaped by fiscal instruments in the polish transport sector. Overall, the findings indicate that fiscal dynamics can transmit into the energy and environmental domains, although the strength and predictability of these links depend on how public resources are allocated.

The conducted IRF analysis and observed response patterns suggest that some of the system dynamics are shaped not only by statistical interdependence, but also by underlying institutional and behavioral factors. This is particularly evident in the time-lagged and persistent reactions observed for some variables. In the case of the delayed response of government revenues (GREV) to a shock in transport energy consumption (TFECT), one explanation is the structure of the Polish tax system. While fuel excise is collected immediately upon sale, other major fiscal revenues, such as VAT or CIT, are subject to monthly or quarterly settlement cycles. As a result, it takes time for increased transport activity and fuel use to be reflected in government accounts. Additionally, rising energy consumption may stimulate broader economic activity in sectors like logistics or retail, which generates taxable value with a certain delay due to accounting practices and reporting periods. These factors help explain why the fiscal response becomes visible only after a few periods. When it comes to the prolonged effect of carbon dioxide emission shocks (CO_2T), which lasts for more than six periods, the key reasons are related to technology and cost barriers in the transport sector. Fossil fuels still dominate the energy mix in transport, and the transition to low-emission technologies, such as electric vehicles, is progressing slowly. This is due to several constraints, including: the limited availability of public charging stations (particularly outside major cities), relative high purchase costs of low-emission vehicles despite existing subsidies and also administrative delays in processing support programs. There are also behavioral aspects involved—both transport users and service providers often postpone switching to cleaner alternatives because of high up-front costs, uncertainty about future regulations, or long lifespans of current using fleets. These elements together contribute to the inertia of the system and explain why the effects of a CO_2 shock are more persistent than those of other variables. These patterns show that the dynamics captured in the model are shaped not just by statistical relationships between energy use, emissions, and fiscal outcomes, but also by real-world aspects and constraints, such as how taxes are settled or how quickly the transport sector can adapt to change.

5. Conclusions

The article analyzes the relationship between the total final energy consumption in transport (TFECT), carbon dioxide emissions from transport (CO_2T), and state budget revenues (GREV) in the context of Poland. The Johansen cointegration method and the associated test statistics, Trace and Max-Eigenvalue, were used. After identifying the existing cointegrating relationships in the analyzed time series, the Impulse Response Function (IRF) was also calculated to gain a deeper understanding of the short- and long-term dynamics between the series, as well as to identify the main transmission channels (i.e., the shocks in the system). The conducted study revealed that the total final energy consumption in transport (TFECT) is a major determinant of both carbon dioxide emissions (CO_2T) and state budget revenues (GREV). Therefore, an increase in energy consumption in transport not only leads to higher emissions but also affects the funds flowing into public accounts. The CO_2T series reacts to TFECT but also to its own shocks, which suggests a self-reinforcing effect in carbon dioxide emissions. The GREV series is strongly linked to TFECT but reacts less predictably to other time series variables. Considering the results obtained, it can be concluded that in Poland, reducing total energy consumption in transport could be an effective way to reduce carbon dioxide emissions from transport activities. Regulations and changes in fiscal policy, including fuel or emission taxes, may impact CO_2 emissions from transport, but the effect is not immediate and spreads over time. The scale of these changes, therefore, depends on long-term government strategies. State budget revenues are also significantly linked to energy consumption in transport, suggesting that tax policies related to transport activities may have a substantial impact on public finances.

The conducted analyses confirm the research hypotheses formulated in the introduction of this study. The first hypothesis, regarding the existence of long-term relationships between energy consumption, CO_2 emissions, and government revenue, is supported by the results of Johansen's cointegration test and the Vector Error Correction Model. The second hypothesis, concerning the direction and nature of these dependencies, is also validated. The impulse response analysis (IRF) shows that an increase in energy consumption in transport leads to a rapid rise in CO_2 emissions, and affects public revenue, albeit with a certain delay. This indicates that the analyzed variables are interconnected over the long term, with varied intensities and time dynamics. These findings also have practical implications for public policy in Poland. In recent years, government initiatives have included a proposed environmental tax on internal combustion vehicles, originally scheduled to come into force in 2026, with rates depending on the EURO emission standard met by the vehicle. At the same time, increasing attention is being paid to an alternative approach emphasizing financial incentives instead of consumer costs. For instance, government subsidies of up to 40,000 PLN are currently available for the purchase of electric vehicles. Such measures are consistent with the directions outlined in the Energy Policy of Poland until 2040 (EPP2040), which emphasizes the development of electromobility, improved energy efficiency, and the decarbonization of the transport sector. An integrated fiscal and environmental approach to transport policy could play an important role in supporting these strategic goals. The results of this study can contribute to the evaluation of both cost-based and incentive-based strategies. On the one hand, increasing fuel taxes may help reduce energy consumption and CO_2 emissions while providing additional public revenue. On the other hand, incentive-based programs require careful fiscal planning but may more effectively accelerate the adoption of low-emission technologies. In light of findings, a balanced approach that combines fiscal and environmental objectives appears to be the most appropriate. Recommended directions should include: (1) fuel taxation based on emission intensity, (2) allocating transport-related tax revenues to the development of sustainable infrastructure, (3) supporting the sector's transformation through targeted tax relief and subsidies for low-emission technologies.

In addition to general fiscal instruments, the adjustment of policy to the national institutional context is of particular importance. In the case of Poland, it is worth considering, among other things, partial redirection of fuel tax revenues to local governments. Currently, fuel tax is set centrally, but local transport is mainly financed by local governments. The introduction of a registration tax linked to CO_2 emissions could be considered (as in Germany or France), although it would be necessary to take into account the total emissions over the entire life cycle of the vehicle. It is also worth postulating better use of EU ETS funds in the transport sector, which are currently directed to a limited extent to decarbonization of transport in Poland, ensuring their greater allocation to the modernization of public rolling stock, support for electromobility or expansion of charging infrastructure. In the context of restrictions resulting from the expenditure rule and the fiscal situation, it is recommended to introduce instruments with high fiscal efficiency, i.e., those that have a low budget cost in relation to environmental effects (e.g., tax reliefs instead of direct subsidies, public-private partnerships).

This study has several limitations. First, the temporal scope of the analysis was limited to the period 1990–2022, reflecting the availability of consistent and reliable macroeconomic and sectoral data over a politically and institutionally stable period. Earlier data were excluded due to concerns about comparability and the structural differences in the economic system prior to the early 1990s. The selected time frame ensures a uniform analytical foundation based on sources from official statistics and recognized international institutions. Second, the analysis focuses on three main variables: total final energy consumption in transport, CO_2 emissions from transport, and government revenues. This choice was motivated by the need to maintain model clarity and long-term data homogeneity. Nevertheless, other factors, such as fuel prices, legal and fiscal reforms, macroeconomic shocks, or technological change, may also influence the relationships under investigation. Additionally, the impact of external shocks, such as geopolitical tensions, crises, or EU climate policies, could introduce volatility into the system that is not fully captured by the model structure. Future studies could incorporate time-varying parameters to better account for such dynamics. Third, the present analysis treats the transport sector as a whole, without disaggregating passenger and freight transport. However, these subsectors may differ in their contributions to energy consumption, emissions, and fiscal outcomes. Differentiating between them in future research could provide a more detailed understanding of the drivers and policy implications within the transport domain. Finally, while the Johansen cointegration approach used in this study is appropriate for assessing long-run relationships among integrated variables, it does not account for possible structural breaks or nonlinear effects. Given Poland's significant institutional and policy transformations during the analyzed period, future research could benefit from applying complementary techniques, such as structural break tests (e.g., Zivot-Andrews) or ARDL-type models. These extensions would provide a broader analytical perspective while building on the solid empirical basis established in the present study. Generally, these limitations do not undermine the validity of the current findings but rather delineate the scope and applicability of the results. At the same time, they point to promising directions for future research.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller test
CBAM	Carbon Border Adjustment Mechanism
CIT	Corporate Income Tax
CO_2	Carbon Dioxide
CO_2T	Carbon Dioxide Emissions from Transport
EDGAR	Emissions Database for Global Atmospheric Research
EPP2040	Energy Policy of Poland until 2040
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GREV	Government Revenue
IEA	International Energy Agency
IMF	International Monetary Fund
IRF	Impulse Response Function
KPSS	Kwiatkowski–Phillips–Schmidt–Shin test
NO_X	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
PLN	Polish Zloty
PM	Particulate Matters
PP	Phillips–Perron test
RLM	Restricted Linear Model
TFECT	Total Final Energy Consumption in Transport
VAR	Vector Autoregressive Model
VAT	Value-Added Tax
VECM	Vector Error Correction Model

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Passenger Air Transport in Poland and Selected European Countries in the Face of COVID-19: A Post-Pandemic Comparative Analysis

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Abstract

Poland, as an important transit hub in Europe, has experienced a dynamic increase in the significance of air transport in recent years. However, the outbreak of the COVID-19 pandemic in 2020 led to a severe collapse of passenger aviation worldwide. The aim of this study was to assess the condition of the passenger air transport market in Poland against the background of selected European countries in connection with the disruptions caused by the pandemic. The Holt–Winters models, based on pre-pandemic data, made it possible to forecast passenger transport volumes in the absence of the crisis and compare them with actual values to estimate losses and the extent of recovery. In the first three months after the outbreak, passenger losses ranged from 7.8 million in Sweden to 13.5 million in Portugal, while Poland recorded 10.9 million; after one year, cumulative losses in Poland reached 44.5 million. In addition, the pace of restoration of selected markets was evaluated. In 2022, Poland reached levels of up to 145% of its reference value, indicating one of the strongest restoration dynamics among the analyzed countries. The results show that all markets experienced sharp declines followed by a comparable rate of growth. The findings confirm Poland's strengthening position in the European air transport system and highlight the need to build resilience to potential future crises.

Keywords: civil aviation; passenger air transport; COVID-19 pandemic; epidemic threats; transport resilience; Holt-Winters method; forecasting; time series analysis

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1. Introduction

Air transport plays a special role in the movement of passengers due to its ability to provide comfortable travel over long distances in a relatively short time [1]. For this reason, it is an attractive mode of transport for all travelers, regardless of whether they travel for personal, tourist, or business purposes, which in turn positively contributes to increased mobility and economic development. Poland, as an important transit hub in Europe, has in recent years experienced a dynamic increase in the importance of air transport. However, the outbreak of the COVID-19 pandemic in March 2020 led to serious disruptions in passenger aviation [2]. This was primarily the result of the progressively introduced restrictions aimed at limiting the spread of the virus. Self-isolation, social distancing, mandatory quarantines, as well as remote work and education, had a clear impact on the functioning and activity of the population [3]. Numerous restrictions and the need to adapt lifestyles to completely new conditions resulted in a decline in mobility and a reduction in demand for passenger transport. Moreover, fears of possible contact with infected individuals in public spaces caused people to more frequently choose individual means of transport, avoiding public transportation [4]. In addition, many people abandoned international travel in favor of local trips [5]. Thus, the pandemic period translated into changes in transport mode preferences and affected travel patterns. This situation was reflected in the functioning of passenger air transport markets worldwide, including in Europe, and consequently also in Poland [6]. The number of flights decreased, interest in international travel declined, and airlines were forced to adapt their operations to a new and challenging reality [7]. Given the situation at that time, both at the national and international levels, the aim of this study was to assess the condition of the passenger air transport market in Poland against the background of selected European countries in connection with the disruptions caused by the COVID-19 pandemic. The research is based on two key research questions:

- How did the COVID-19 pandemic affect the performance of passenger air transport in Poland compared with selected European countries?
- From the post-pandemic perspective, how did the process of recovery of the passenger air transport market in Poland proceed in relation to other European countries?

The article presents a comparative analysis of the condition of passenger air transport in Poland and selected European countries during the COVID-19 pandemic disruption, applying the Holt-Winters forecasting method to assess losses and the extent of recovery across individual markets. The study provides evidence that the aviation sector in Poland, similarly to other countries, experienced a dramatic decline in the number of passengers carried. At the same time, it demonstrated a recovery dynamic comparable to that of markets with stronger economies, which is a positive phenomenon. The results highlight the importance of the transport market's resilience to epidemic-related crises and indicate that Poland's strategic location and the ongoing development of its infrastructure may foster long-term growth. The paper also emphasizes the need to develop strategies that enhance the stability and preparedness of the aviation market for future threats of a similar nature.

This study contributes to the existing research by applying a single forecasting approach consistently across several European aviation markets (Poland, Portugal, Sweden, Norway, Switzerland), by quantifying the scale of COVID-19 pandemic-related changes using pre-pandemic trends and seasonal patterns, and by comparing differences in the extent and pace of restoration between air passenger transport markets with distinct structural characteristics.

This publication consists of several sections. The introduction presents a general outline of the study, including its purpose and research questions. This is followed by a literature review focusing on publications addressing the impact of the COVID-19 pandemic on the economy and the transport sector, as well as studies employing mathematical methods to analyze transport disruptions resulting from the epidemic crisis. Subsequently, the materials and methods applied in the study are described. Section 4 constitutes the core of the paper and includes the review and selection of markets for comparison, the modeling and forecasting of passenger numbers in selected countries, along with a supplementary comparison of alternative forecasting approaches to verify the robustness of the results, and a comparative analysis of market losses and recovery. and a comparative analysis of market losses and recovery. Finally, the conclusions are presented, summarizing the study's findings and key results.

2. Literature Review

The COVID-19 pandemic became a phenomenon that was closely monitored and analyzed, which was reflected in the growing number of published reports, information bulletins, and scientific papers focused on this threat. The global spread of the SARS-CoV-2 virus shook the world economy, leading to its prolonged destabilization. This situation was reflected in serious disruptions to transport systems [8], particularly affecting passenger air transport. Initially, airlines attempted to maintain regular flight schedules in order to meet public demand. However, it was soon observed that a characteristic feature of COVID-19 was the rapid transmission of the virus across different regions of the world [9]. Most countries recognized international and regional air connections as one of the main routes for pathogen transmission [10]. Therefore, governments around the world decided to introduce travel restrictions to curb the spread of the virus [11]. In response to the threat, there were increasing instances of countries refusing to accept flights from states and regions with high infection rates. International borders began to close, which not only made foreign destinations inaccessible to visitors but also created difficulties for people attempting to return to their home countries [12,13]. Air transport also became less attractive due to the requirements imposed by some governments on travelers. These often involved mandatory testing, the obligation to present a vaccination certificate, or enforced quarantine.

Another important factor influencing the condition of passenger air transport was the restrictions imposed on the hotel industry. The availability of hotel facilities became strictly dependent on government decisions, which varied according to the current epidemiological situation. Hotels were alternately closed and reopened for specific groups. This made it impossible to plan vacations or business trips in advance, which ultimately led to a decline in interest among passengers traveling for tourism and business purposes [14].

Other studies have shown that psychological factors were also significant for the demand for air travel. It was found that the spread of SARS-CoV-2 caused concern among many people, and in extreme cases even fear of infection through close contact with others in airports or on airplanes [15]. Flights were increasingly canceled, or travelers chose alternative and seemingly safer modes of transportation. The development of video-conferencing technology also contributed to the decline in the number of passengers carried, as it made it possible to conduct business and social activities without the need for physical travel [16,17].

All of the above-mentioned factors led to a severe decline in travel demand, thereby generating significant disruptions in passenger aviation [18]. As a result, the analytical approach has become a popular direction in the literature, aiming to illustrate the broad impact of the COVID-19 pandemic on transport. Researchers frequently apply mathematical methods to examine the functioning of transport processes under crisis conditions, including passenger air transport. Existing studies can generally be examined in relation to three aspects: the research region, the applied methods, and the main areas of application.

A significant portion of publications focuses on Europe. For example, in Poland researchers employed various time series analysis methods, ranging from the discrete wavelet transform (DWT) and statistical tests used to identify seasonality, to exponential smoothing and Fourier spectral analysis. These approaches made it possible not only to capture the sharp declines in air traffic [19] but also to indicate differences in the number of passengers handled at specific airports (e.g., Szczecin Goleniów) [20]. Other studies focused on assessing the variation in passenger transport losses among selected EU countries in the years 2015–2021 [21], as well as on a multidimensional comparative analysis of the Polish and German markets in 2020–2022, highlighting different initial recovery paths following the outbreak of the pandemic [22]. In Germany, additional research examined the financial condition of airports (Frankfurt, Munich), using stochastic equations with the standard Wiener process to forecast EBITDA [23].

In Latin America, specifically in Brazil, the use of Bayesian structural time series (BSTS) models made it possible to estimate the impact of COVID-19 on air travel demand and the resulting changes in CO_2 emissions [24]. In Colombia, BSTS models were applied to develop medium- and long-term forecasts, confirming that both passenger and freight transport demand would return to pre-pandemic levels within the next few years [25].

In Asia, research conducted on Beijing Daxing International Airport (China) was based on machine learning algorithms (the LightGBM model with SHAP values), incorporating pandemic-related variables to forecast short-term daily passenger flows at the airport terminal [26]. Meanwhile, in Turkey, actual air traffic density was compared with forecasts obtained from two models—SARIMA and the multilayer perceptron (MLP). Both models proved effective and demonstrated a significant decline in air traffic in Turkish airspace, dependent on pandemic restrictions [27]. Other comparative studies based on ARIMAX models indicated that the Asia–Pacific macroregion experienced a short-term but intense shock, followed by a rapid recovery of the air transport sector [28].

North America was primarily analyzed within comparative studies involving other parts of the world. SARIMA models, based on data from 2010 to 2019, were used to estimate monthly passenger traffic in the United States, European countries, and China from January 2020 to December 2022, assuming the absence of the COVID-19 pandemic. The results showed that in the United States and Europe, a gradual improvement in transport volumes was observed in the months following the outbreak of the pandemic, whereas in China, a clear decline in traffic occurred in 2021–2022 due to a sharp increase in the number of infections [29]. Furthermore, another comparative analysis demonstrated that in the United States, the impact of the pandemic was relatively uniform, and the recovery of domestic connections progressed faster than in Europe [30].

In the case of global-scale studies, it can be observed that they focused on analyzing virus transmission mechanisms in the context of passenger air travel. To forecast the risk of SARS-CoV-2 transmission, survival models (e.g., the Cox model, inverse distance model) and the concept of "effective distance" in the air transport network were applied [31]. Another study estimated the relationship between the volume of passenger air traffic and the number of COVID-19 cases worldwide, using, among others, Poisson regression models (PM, QPM) [32].

As shown, the literature employs a variety of analytical approaches, ranging from classical statistical methods and time series analyses to machine learning and network-based models. Such methods make it possible not only to analyze sudden drops in demand but also to forecast recovery scenarios, assess the effects of pandemic restrictions, evaluate economic impacts and analyze environmental consequences [33,34].

In parallel to studies focused on the effects of the COVID-19 pandemic, an increasing number of publications examine long-term changes taking place in the aviation sector in connection with climate-policy commitments and decarbonization targets [35,36]. These works point to the growing importance of technological developments, the role of sustainable aviation fuels and the use of market-based instruments, including emissions trading and carbon pricing, in shaping the sector's future regulatory and cost environment [37,38]. In the European context, these issues are reflected in the Fit for 55 package, the ReFuelEU Aviation regulation, which introduces mandatory SAF blending levels [39], as well as the gradual tightening of the EU Emissions Trading System (ETS) for aviation [40,41]. Scenario-based studies also show that achieving net-zero climate impacts will require improvements in energy efficiency, the use of alternative fuels and operational adjustments, and may lead to higher operating costs and ticket prices, while only moderately affecting overall demand for air travel [42,43]. This different strand of work highlights that contemporary aviation is subject to multiple, overlapping pressures, with the pandemic representing only one albeit highly disruptive factor.

However, there is a lack of studies that, from a post-pandemic perspective, compare the condition of passenger air transport in Poland with that of other European countries using forecasting models such as the Holt–Winters method to assess the losses caused by the COVID-19 crisis and the dynamics of market recovery. The identified research gap served as the starting point for this study, which is focused on analyzing the impact of the pandemic on transport performance and the course of recovery processes in passenger air transport markets in Poland and selected European countries.

3. Materials and Methods

The entire research process was structured in the form of a three-layer methodological framework. This structure includes the stages of data preparation, mathematical model development and validation, as well as the analysis and interpretation of the obtained results. Figure 1 illustrates this framework by clearly outlining the sequential structure of the study and the relationships between its stages, providing a clearer context for the applied approach.

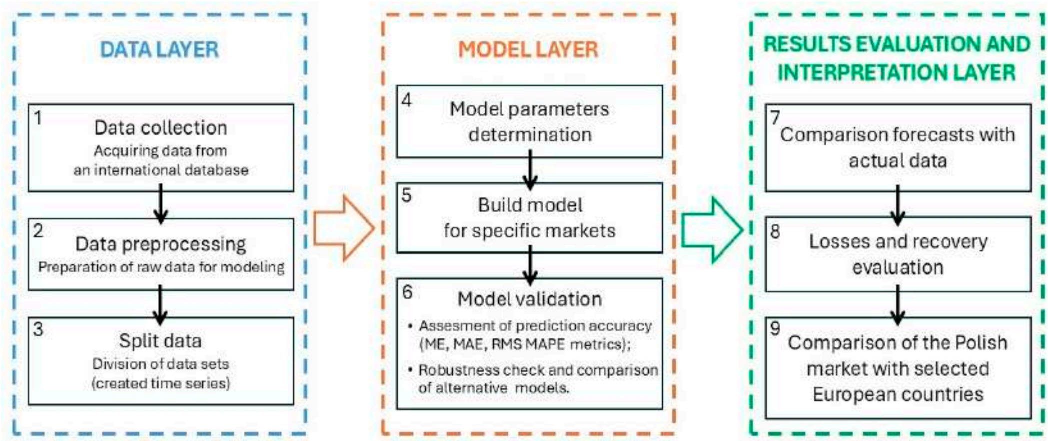


Figure 1. Three-layer methodological framework of study outlining the sequence from data preparation to model development and results analysis.

The study, starting from data layer, utilized the database of the Statistical Office of the European Union (Eurostat), which contains extensive data on transport activities in Europe. The research was based on the dataset "Air passenger transport by type of schedule, transport coverage and country", which was adjusted in terms of geopolitical scope, time range, and available measurement units [44]. As a result, monthly data were obtained on the total number of passengers transported by air in 30 European countries (the EU27 region plus Iceland, Norway, and Switzerland). The study covered the period from January 2004 to March 2024, as only for this time range was a complete set of monthly data available for all 30 countries. Subsequently, taking into account the long-term transport characteristics of individual national markets, countries with results comparable to those of Poland were identified. In addition, a contextual analysis of economic and infrastructural conditions was carried out to better understand the specific features of each market. In the next stage of the research, the collected data were used to construct time series representing the number of passengers transported by air in the selected countries. Each of the time series was then divided into two subsets, with the outbreak of the COVID-19 pandemic in March 2020 serving as the point of division. The first subset was used to develop a mathematical model and to generate forecasts for the period following the emergence of the epidemic threat. The second subset served as a reference dataset, enabling the estimation of losses through the comparison of the actual state (reflecting the declines caused by the pandemic) with the forecasts based on data from before March 2020, which represented the potential level of air transport in the absence of disruptions.

The next layer of the study (model layer) involved the development of mathematical models describing the number of passengers transported by air. To identify and predict temporal changes, time series models are used, as they make it possible to describe the nature of the analyzed process, identify its deterministic components, and represent the process as a function consisting of such elements as a trend, seasonal fluctuations, cyclical variations, and random disturbances [45]. Identification of the individual components and the internal dynamics of a time series enables the forecasting of its future values [46]. In this study, the Holt–Winters model was applied, as it is suitable for time series that exhibit a trend, seasonal fluctuations, and random variations. Due to its flexibility, this model is widely used by researchers across various fields. For instance, in industry, it can be used for forecasting product sales [47], or electricity generation [48], while in demography it is applied to predict birth and death rates [49]. Another area of application involves the analysis of developmental trends and the forecasting of the spread of epidemic threats such as COVID-19 [50]. Moreover, the Holt–Winters method is also used in transport process modeling, including analyses of vehicle volumes and related congestion, road traffic safety studies, and forecasts of passenger transport demand [51,52]. There are two variants of this model that differ in the nature of their seasonal component. The additive model is preferred when seasonal fluctuations remain approximately constant throughout the series, whereas the multiplicative model is more suitable when seasonal fluctuations change proportionally to the level of the series [53,54]. In this study, for each of the analyzed air transport markets, a multiplicative model was applied, consisting of the forecasting equation Y^*_{t+m} (1) and three smoothing equations: the level L_t (2), the trend B_t (3), and the seasonality S_t (4):

$$Y^*_{t+m} = \frac{L_t + B_t * m}{S_{t-s+m}} \tag{1}$$

$$L_t = \alpha \frac{Y_t}{S_{t-s}} + (1-\alpha)(L_{t-1} + B_{t-1}) \tag{2}$$

$$B_t = \delta(L_t - L_{t-1}) + (1-\delta)B_{t-1} \tag{3}$$

$$S_t = \gamma \frac{Y_t}{L_t} + (1-\gamma)S_{t-s} \tag{4}$$

where:

α, δ, γ—exponential smoothing coefficients such that $\alpha,\ \delta,\ \gamma\epsilon(0;1)$;

Y_t—actual value at time t;

S—length of the seasonality cycle (for monthly data L = 12);

m—forecast horizon [55].

In the adopted approach, the exponential smoothing coefficients α, δ, γ were selected to achieve a high fit of the model to the actual data by minimizing the Mean Absolute Percentage Error (*MAPE*) [24]:

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{Y_t - Y^*_t}{Y_t}\right| * 100\ \ [\%] \tag{5}$$

where:

Y^*_t—forecast value at time t;

Y_t—actual value at time t;

n—number of observations.

The Holt–Winters models were estimated using an automatic optimization procedure, which determines the smoothing parameters (α, δ, γ) by minimizing the in-sample forecast errors. For each country, several candidate specifications generated by the software were compared, and the final model was selected based on the lowest *MAPE* value. Model validation was carried out by applying the set of accuracy metrics, by comparing AIC values across specifications, and by analyzing residual behavior using standard diagnostic tests, including the Shapiro–Wilk test. In addition, the coefficient of determination (R^2) was included as a supplementary indicator of the overall fit of each model.

To present these diagnostic results explicitly, the accuracy of each model was assessed using standard error metrics. Besides *MAPE*, the Mean Error (*ME*), Mean Absolute Error (*MAE*), and Root Mean Square Error (*RMSE*) were computed according to Formulas (6)–(8):

$$ME = \frac{1}{n}\sum_{t=1}^{n}(Y_t - Y_t^*), \tag{6}$$

$$MAE = \frac{1}{n}\sum_{t=1}^{n}|Y_t^* - Y_t|, \tag{7}$$

$$RMSE = \sqrt{\sum_{t=1}^{n}\frac{(Y_t^* - Y_t)^2}{n}}, \tag{8}$$

where:

Y_t^*—forecast value at time t;

Y_t—actual value at time t;

n—number of observations.

Lower error values indicate that the model forecasts are closer to the actual observations, which translates into higher forecast accuracy and, consequently, greater predictive capability of the model [56]. Furthermore, to compare the goodness of fit and complexity of alternative models, the Akaike Information Criterion (*AIC*) was applied, the value of which was determined using the following formula:

$$AIC = 2k - 2ln(L), \tag{9}$$

where:

k—number of parameters in the model;

L—reliability function.

Lower *AIC* values indicate a better trade-off between model fit and the number of estimated parameters. This ensured that the model selection was not solely the result of forecast error minimization, but also maintained a balance between accuracy and model complexity. At this stage of the study, the Shapiro–Wilk test (*W*) was also performed to assess whether the residuals followed an approximately normal distribution [57].

The coefficient of determination (R^2) was also calculated as a supplementary measure of overall model fit. It was computed using the standard formulation based on the sum of squared residuals (SSE) and the total sum of squares (SST) [58]:

$$R^2 = 1 - \frac{\sum_{t=1}^{n}(Y_t - Y_t^*)^2}{\sum_{t=1}^{n}(Y_t - \overline{Y})^2} \tag{10}$$

where:

Y_t—actual value at time t;

Y_t^*—forecast value at time t;

$\overline{Y}$—mean of all observations;

n—number of observations.

Additionally, for robustness purposes, several alternative forecasting models (SARIMA [59], BSM [60,61], TSLM [62], Random Forest [63,64]) were estimated using the same pre-pandemic dataset and identical accuracy metrics. These models served only as a supplementary check of the stability of the results.

The final stage (results evaluation and interpretation layer) involved the analysis and interpretation of the results obtained from the mathematical models in order to evaluate and compare the condition of selected passenger air transport markets disrupted by the epidemic threat. The forecasts derived from the Holt–Winters models were used to determine the losses (L_m) incurred during specific periods following the outbreak of the COVID-19 pandemic, which were calculated as follows:

$$L_m = \sum_{i=1}^{m} PF_i - \sum_{i=1}^{m} PA_i, \tag{11}$$

where:

L_m—passenger losses in the m months since the outbreak of the pandemic;

m—number of months since the outbreak of the pandemic;

PF_m—projected number of passengers transported m months after the outbreak of the pandemic;

PA_m—actual number of passengers transported m months after the outbreak of the pandemic.

Next, the extent of loss recovery (R_m) was determined in the corresponding periods:

$$R_m = \frac{\sum_{i=1}^{m} PA_i}{\sum_{i=1}^{m} PF_i} \times 100\ [\%], \tag{12}$$

where:

R_m—extent of loss recovery in the period of m months since the outbreak of the pandemic;

m—number of months since the outbreak of the pandemic;

PA_m—actual number of passengers transported m months after the outbreak of the pandemic;

PF_m—projected number of passengers transported m months after the outbreak of the pandemic.

Additionally, to obtain a more comprehensive picture, the actual transport performance in the subsequent months following the announcement of the pandemic was compared with the data from the beginning of 2020, which made it possible to assess the pace of market restoration in each of the analyzed countries. For this purpose, the following formula was applied:

$$D_z = \frac{Y_z}{J} \times 100\ [\%], \tag{13}$$

where:

D_z—ratio of the number of passengers carried in month z relative to January 2020;

z—months following the outbreak of the pandemic, starting in April 2020;

Y_z—actual number of passengers in month z;

J—actual number of passengers in January 2020.

Furthermore, for the results obtained in this way, color mapping was applied, assigning appropriate colors to three percentage value ranges:

- red ($\leq$35%)—very low or low level of market restoration;

- yellow (35.1–85%)—medium level;
- green (≥85.1%)—high level, close to or exceeding the level from January 2020.

The introduced classification facilitated the systematic interpretation of the data, enabling the identification of patterns and the comparison of the pace of restoration between individual air transport markets.

The modeling within this study was carried out using Statistica software (version 13.3, StatSoft/TIBCO, Hamburg, Germany) [65] and R Core software (version 4.4.3, R Core Team/R Foundation for Statistical Computing, Vienna, Austria) [66] with packages that provide a set of algorithms for data preprocessing, time series forecasting and machine learning. All visualizations were prepared in MS Excel. The approach described in this section made it possible to conduct a comparative analysis of the condition of air transport markets disrupted by the outbreak of the COVID-19 pandemic, as well as to assess Poland's situation relative to other European countries.

4. Results and Discussion

4.1. Selection and Characteristics of Markets Included in the Analysis

The study began with the acquisition of data from the Eurostat database containing information on air passenger transport in 35 European countries. The dataset was subsequently adjusted in terms of geopolitical scope, time horizon, and available measurement units. Verification of the completeness of monthly data made it possible to determine a study period that ensured the largest number of markets suitable for comparison. The period from January 2012 to March 2024 was adopted, excluding countries with data gaps for these dates—the United Kingdom, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia. As a result, monthly data were obtained for the total number of passengers transported by air in 30 European countries, specifically in the European Union member states (EU27) as well as Iceland, Norway, and Switzerland. The prepared dataset reflected both long-term transport trends and distinct disruptions in the trend caused by the outbreak of the COVID-19 pandemic, forming the starting point for further analysis. Figure2provides a comparative overview of monthly passenger volumes in 2012–2024 across 30 European countries (EU27 plus Switzerland, Norway, and Iceland), showing both the typical seasonal patterns and the sharp structural break in 2020 caused by the pandemic.

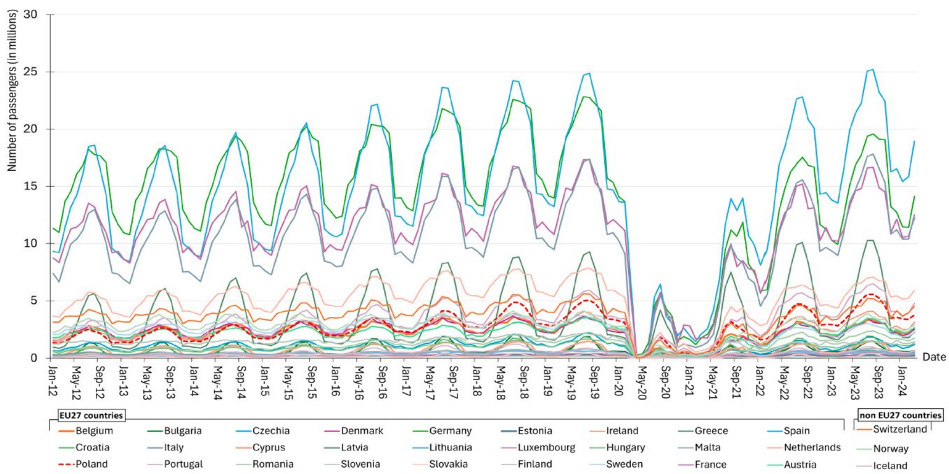


Figure 2. Overview of monthly passenger air transport volumes across 30 European countries in 2012–2024.

Subsequently, from the dataset comprising 30 European countries, a comparative group was selected based on the similarity of long-term passenger traffic volumes to those observed in Poland prior to the pandemic. Before the final selection, several other medium-sized markets with comparable monthly passenger volumes in the last pre-pandemic years were also taken into consideration (among others Ireland, Belgium, Denmark and Austria). The final choice of countries was made according to three criteria: (i) full availability and internal consistency of the Eurostat series for 2012–2024, (ii) the most comparable whole-term passenger volumes, and (iii) the possibility of capturing structurally distinct configurations of national air transport markets. In this respect, the inclusion of Portugal, Sweden, Norway and Switzerland provides a complete set of reference countries that, despite having pre-pandemic passenger volumes broadly comparable to those of Poland, represent different long-term demand structures shaped, respectively, by tourism activity (Portugal), domestic network needs (Sweden and Norway), and internationally oriented hub operations (Switzerland). Such structural variation within a volume-comparable group makes it possible to interpret Poland's dynamics more reliably by contrasting its trajectory with markets exposed to different dominant drivers of passenger air transport. The monthly passenger air transport volumes in 2012–2024 for these countries are presented in Figure3 to illustrate their relevance as reference markets. The monthly passenger air transport volumes in 2012–2024 for these countries are presented in Figure3to demonstrate their relevance as comparable markets.

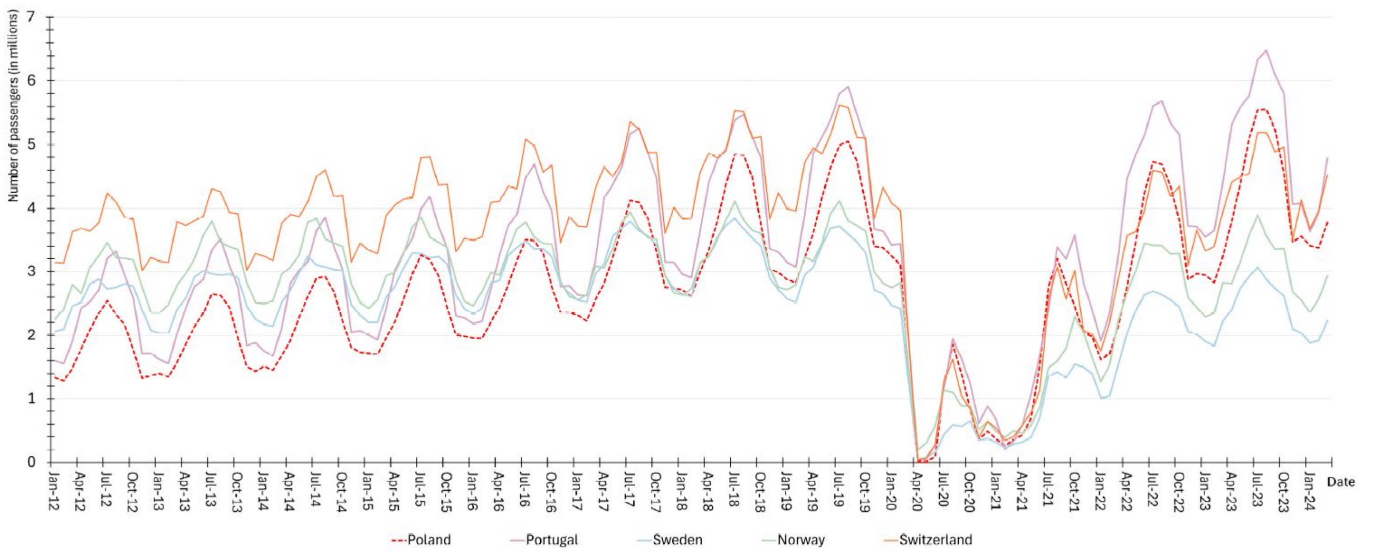


Figure 3. Overview of monthly passenger air transport volumes in 2012–2024 for Poland and markets selected for further analysis.

In addition, key demographic, economic, and infrastructural indicators were compiled to characterize the structural profile of the selected countries and to support the justification for their inclusion in the subsequent stages of the analysis. These characteristics provide essential background for interpreting the comparative results discussed later in the study. The detailed values of these indicators are summarized in Table1.

As shown in Table1, among the countries included in the further stages of the study, there is a clear differentiation, particularly in terms of population size, economic performance, land area, and the number of airports. These differences reflect the specific characteristics of individual markets, thereby increasing the comparative value of the entire analysis. Although Poland has a relatively lower GDP per capita compared to the Scandinavian countries and Switzerland, in 2023 it recorded a high passenger volume of over 50 million people. This result was comparable to the Swiss market and exceeded the volumes achieved in Sweden and Norway. This indicates that after the COVID-19 pandemic, Poland has been consistently becoming an increasingly important transport hub in Central Europe, mainly due to the expansion of international routes offered by low-cost airlines, as well as the strengthening position of the national carrier LOT Polish Airlines. Among the analyzed countries, the highest passenger transport volume was recorded in Portugal, which handled 61.1 million passengers in 2023—about 11 million more than Poland—despite having a population more than three times smaller. This high level of air traffic primarily results from the structure of Portugal's economy and its geographical location. The country is strongly tourism-oriented, and its attractiveness as a leisure destination means that a significant share of passenger transport is generated by foreign visitors. In the case of Sweden and Norway, it can be observed that compared to Poland, these countries have a much higher GDP per capita, as well as exceptionally well-developed domestic air transport networks—with 41 and 45 civil airports, respectively. The large number of airports demonstrates that in both countries, air transport plays a crucial role not only in international connections but also as an essential mode of internal communication within the Scandinavian region, characterized by vast territory, low population density, and geographical barriers such as mountain ranges and numerous fjords. Meanwhile, Switzerland, despite having the smallest area and population among all the compared countries, recorded nearly 52 million air passengers in 2023, according to the available data. This high level of passenger transport is directly related to Switzerland's significance on the international stage, where its role as a financial and institutional center is combined with a well-developed transport infrastructure. Moreover, the strong position of the national carrier SWISS, which is part of the German Lufthansa Group, further reinforces this effect.

Table 1. Demographic, economic, and infrastructural characteristics of Poland and the markets selected for further analysis.

Country	Poland	Portugal	Sweden	Norway	Switzerland
Population (in millions)	36.69	10.58	10.54	5.52	8.89
Area [km2]	312.696	92.391	450.295	385.207	41.285
GDP per capita (2023) [USD]	22,056.67	27,331.21	55,516.84	87,925.09	99,564.71
Civil airports	15	19	41	45	7
Main airlines	PLL LOT, Enter Air, Ryanair, Wizz Air	TAP Air Portugal, Azores Airlines, Sevenair SA	Scandinavian Airlines (SAS), Norwegian Air Sweden Braathens,	Scandinavian Airlines (SAS), Norwegian Air Shuttle, Widerøe	SWISS, easyJet, Edelweiss Air, Helvetic Airways
Passengers carried by air transport in 2023 (in millions)	50.17	61.10	29.44	36.38	51.95

The conducted selection and analysis of the conditions of individual markets made it possible to establish a comparative perspective for assessing the situation in Poland against other European countries. Therefore, the selection of countries constituted the starting point for the next stage of the study, in which mathematical models were developed to forecast the level of air passenger transport under conditions without disruptions related to the COVID-19 pandemic.

4.2. Modeling and Forecasting of the Number of Carried Passengers in Selected Countries

The application of mathematical modeling enables the study of transport processes under crisis conditions and the assessment of their resilience. In this case, by employing the

Holt–Winters model, forecasts were generated based on pre-pandemic data to determine the potential level of passenger transport in the absence of epidemic disruptions. For all selected countries, the multiplicative variant of the model was applied, as it allows capturing both development trends and the distinct seasonality characteristic of the air passenger transport market. The exponential smoothing coefficients α, δ, and γ were selected in order to achieve a high degree of model fit to actual data by minimizing the Mean Absolute Percentage Error (*MAPE*).

The modeling process began with Poland. The lowest *MAPE* value, amounting to 1.85%, was obtained for the parameters $\alpha = 0.9$, $\delta = 0.1$, and $\gamma = 0.1$. The results indicate a strong agreement between the forecasted and actual values up to the outbreak of the pandemic. However, in the subsequent months, due to COVID-19, a significant deviation became apparent, particularly during the period March–June 2020. Actual passenger transport plummeted sharply, reaching only 10.4 thousand in May 2020, whereas the model predicted a continued upward trend. It is also noteworthy that by mid-2023, the forecasts indicated that the number of carried passengers should exceed the record level of 7 million. It should be noted that this represents a forecasted level reflecting the development potential of the market based on historical data, which in practice may be constrained by various financial, infrastructural, or organizational factors. In this context, particular importance is attached to the implementation of the Central Communication Port (CPK) project, which aims to create a transport hub integrating passenger and cargo air traffic with the rail and road networks. The main component of this project will be a new airport, which is ultimately expected to become the largest hub in Central and Eastern Europe, handling millions of passengers annually and providing long-haul connections [67]. According to the latest forecasts by IATA, CPK will be capable of serving around 32 million passengers in its first full year of operation, and by 2040 this number may increase to as many as 40 million. The investment is expected to significantly enhance Poland's air connectivity, thereby strengthening the country's competitiveness in the European market. It also assumes a high share of transfer traffic and a developed cargo activity, both of which may contribute substantially to overcoming existing limitations and further market growth [68]. Against this background, it is a positive development that since 2022, actual passenger traffic has gradually recovered its typical seasonality, and during the summer peaks of 2022 and 2023, the observed values were already much closer to the optimistic forecasts, indicating market stabilization and a return to a growth trajectory. A comparison of the model values with the actual number of passengers carried by air transport in Poland is presented in Figure 4.

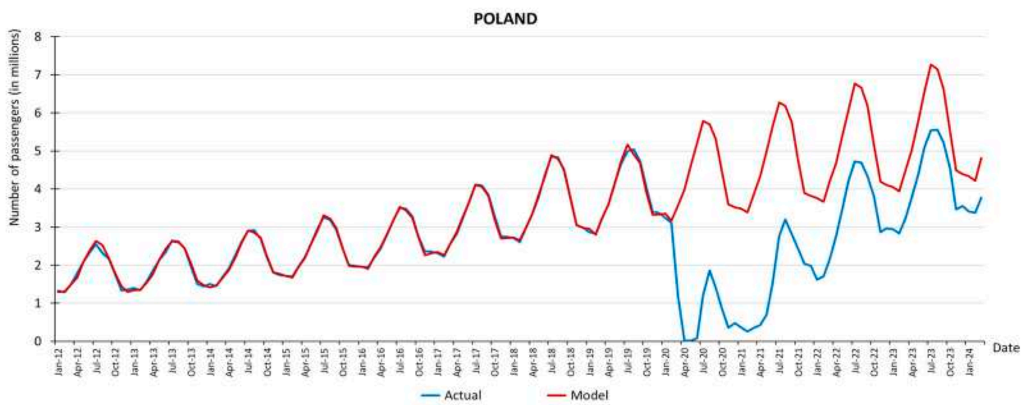


Figure 4. Comparison of model forecasts with the actual number of air transport passengers in Poland.

As part of the verification process, the Shapiro–Wilk test was carried out, and the result ($W = 0.978$, *p-value* = 0.105) confirmed that the residuals followed a distribution close to normal. The obtained *AIC* value of 2466.5 indicates a good model fit with moderate complexity. The R^2 value for the model was 0.99602. In addition, to further assess the forecast accuracy, the *ME*, *MAE*, and *RMSE* metrics were applied, with their low values confirming a high level of model precision (Table 2).

Table 2. Assessment of forecast accuracy in the Holt–Winters model for the Polish market.

Metric	Value
Mean Absolute Percentage Error (*MAPE*)	1.845%
Mean Error (*ME*)	−298.109
Mean Absolute Error (*MAE*)	45,574.277
Root Mean Square Error (*RMSE*)	59,391.479

For the case study of Portugal, the best-fitting model was obtained with the parameters $\alpha = 0.8$, $\delta = 0.1$, $\gamma = 0.1$, yielding a *MAPE* of 1.97%. Similarly to Poland, the forecasts indicated a continued dynamic market expansion, which was abruptly interrupted by the epidemic crisis. The developed model accurately reproduced the characteristics of passenger traffic observed before the COVID-19 pandemic. After the outbreak, the largest discrepancies between the forecasts and actual values occurred during the summer months of 2020 (difference of approx. 16.99 million) and 2021 (difference of approx. 15.28 million). In contrast, during the winter season, the deviations were smaller (around 10.13 million in 2021), reflecting the lower demand for air transport outside the holiday period. Portugal thus represents a market strongly dependent on tourism-driven demand, which was severely constrained by the mobility restrictions and epidemiological safety procedures in force at the time. From 2022 onwards, a gradual restoration of seasonal patterns can be observed, while the still significant differences from the forecasts stem from the fact that the historically based model assumed the achievement of record traffic levels under a no-crisis scenario (Figure 5).

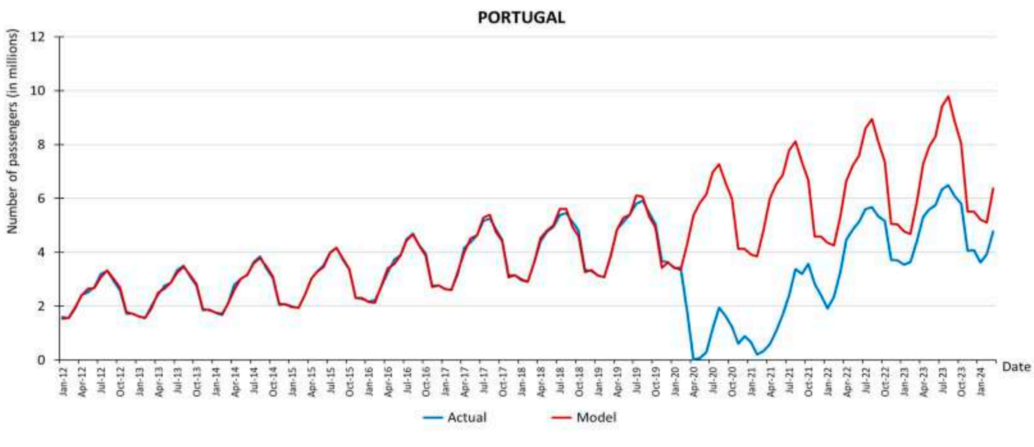


Figure 5. Comparison of model forecasts with the actual number of air transport passengers in Portugal.

As in the previous case, the conformity of the model residuals with the normal distribution was verified. In the Shapiro–Wilk test, the result was $W = 0.982$ with a *p-value* = 0.184. The *AIC* value of 2552.2 indicates a level of model complexity similar to that obtained for the Polish case study. This model achieved an R^2 of 0.9933. In addition to *MAPE*, the values of the *ME*, *MAE*, and *RMSE* were also calculated (Table 3).

Table 3. Assessment of forecast accuracy in the Holt–Winters model for the Portuguese market.

Metric	Value
Mean Absolute Percentage Error (*MAPE*)	1.973%
Mean Error (*ME*)	594.162
Mean Absolute Error (*MAE*)	67,857.894
Root Mean Square Error (*RMSE*)	91,947.498

For Sweden, the best fit for the Holt–Winters model was achieved with the parameters $\alpha = 0.6$, $\delta = 0.1$, $\gamma = 0.1$. The developed model accurately captured both the trend and seasonality of the Swedish passenger market, as evidenced by a low *MAPE* of approximately 1.64%. It is worth noting that even before the pandemic, in 2019, there was a decline in the annual number of passengers compared to the record level of 2018 (a year-on-year difference of about 1.33 million passengers), suggesting that the airline market's performance was also constrained by factors unrelated to the epidemic crisis. In the first half of 2020, similar to the Polish and Portuguese markets, there was a sharp collapse in passenger traffic, resulting from pandemic restrictions and the associated changes in society's travel needs. The 2021–2022 period brought a noticeable recovery, although seasonal peaks were still below those projected under a no-crisis scenario. The turning point came in 2023, as from April onwards, the actual values gradually approached the forecasts, and during the summer, the two series almost completely overlapped. This can be interpreted as a return of the Swedish market to the level of passenger traffic that would have been achieved without pandemic disruptions. This demonstrates the relatively high resilience of Sweden's passenger air transport, largely based on domestic connections. The comparison of model forecasts with the actual number of passengers transported in Sweden is shown in Figure 6.

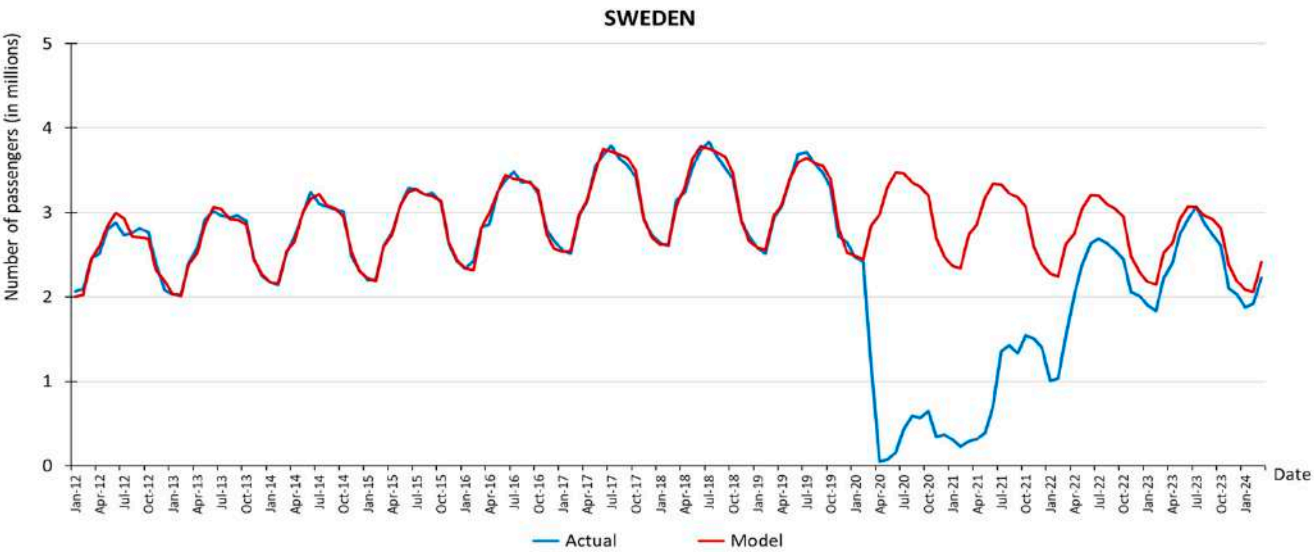


Figure 6. Comparison of model forecasts with the actual number of air transport passengers in Sweden.

Model verification confirmed its validity. The Shapiro–Wilk test statistic was $W = 0.986$ with a *p-value* = 0.363, and the *AIC* was 2471.1. The coefficient of determination (R^2) for this model amounted to 0.98304. Additionally, other error metrics such as *ME*, *MAE*, and *RMSE* also indicate a high accuracy of the forecasts (Table 4).

Table 4. Assessment of forecast accuracy in the Holt–Winters model for the Swedish market.

Metric	Value
Mean Absolute Percentage Error (*MAPE*)	1.635%
Mean Error (*ME*)	−4087.547
Mean Absolute Error (*MAE*)	47,544.672
Root Mean Square Error (*RMSE*)	60,789.824

The Norwegian market was best described by the Holt–Winters model with parameters $\alpha = 0.3$, $\delta = 0.1$, $\gamma = 0.1$. The low *MAPE* of approximately 1.31% indicates that the forecasts obtained were the most accurate among all analyzed cases. Between 2012 and 2019, the market in Norway experienced moderate growth without the significant increases characteristic of countries such as Poland or Portugal. Consequently, forecasts for 2023–2024 assumed only a gradual, mild increase in passenger numbers compared to pre-crisis levels. The initial phase of the pandemic caused a sharp decline in passenger traffic, reaching around 86% in April 2020 compared to March of the same year. The recovery process began in 2021 and, in Norway, it was more dynamic than in Sweden. Seasonal fluctuation amplitudes were more pronounced, and differences between forecasted and actual values decreased more rapidly. From mid-2023 onwards, both series converged significantly, which can be interpreted as a sign of the Norwegian market steadily returning to the pre-pandemic growth scenario. This supports the conclusion that the dominance of domestic flights and Norway's specific geographic conditions made the market relatively less vulnerable to the effects of restrictions on international travel. The comparison of forecasted and actual values for Norwegian passenger air transport is shown in Figure 7.

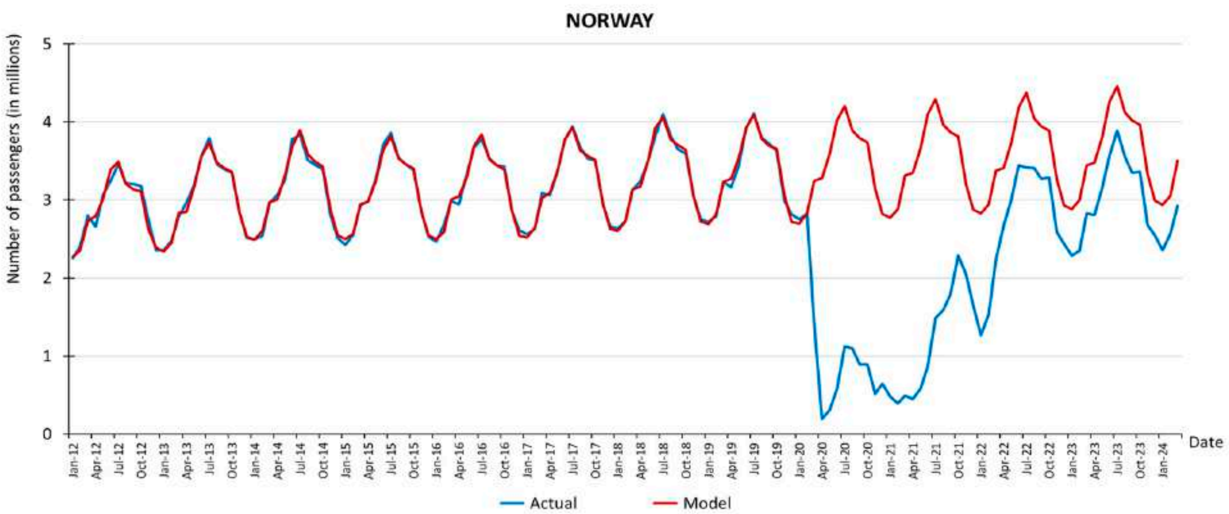


Figure 7. Comparison of model forecasts with the actual number of air transport passengers in Norway.

For this model as well, there is no basis to reject the hypothesis of normality of residuals. The Shapiro–Wilk test statistic (*W*) was 0.988 with a *p-value* = 0.505. The *AIC* value of 2442.7 confirms that the applied model achieves an appropriate balance between goodness of fit and the complexity of its parametric structure. The R^2 for this model reached 0.9878. Moreover, the error metrics *ME, MAE*, and *RMSE*, similarly to *MAPE*, also confirm the high accuracy of the forecasts (Table 5).

Table 5. Assessment of forecast accuracy in the Holt–Winters model for the Norwegian market.

Metric	Value
Mean Absolute Percentage Error (*MAPE*)	1.313%
Mean Error (*ME*)	−597.599
Mean Absolute Error (*MAE*)	40,308.111
Root Mean Square Error (*RMSE*)	52,653.495

The last of the models developed in this study concerned the Swiss market, with parameters set at $\alpha = 0.4$, $\delta = 0.1$, $\gamma = 0.1$, yielding a *MAPE* of approximately 1.43%. A comparison of the forecasted and actual values shows that the Swiss air transport market, similar to Portugal, was heavily dependent on international travel, which led to a sharp collapse immediately after the outbreak of the pandemic. This is confirmed by the difference in the number of passengers carried, which reached 3.94 million during the February–April 2020 period. In 2021–2022, despite visible signs of market recovery, actual passenger traffic remained significantly below the levels projected in a no-disruption scenario. At the beginning of 2023, there was a clear improvement, and from October of the same year, actual values nearly matched the forecasts. This indicates that the Swiss market had returned to its model development trajectory, thereby restoring the potential implied by its pre-pandemic condition. As observed, COVID-19 clearly impacted passenger air transport in Switzerland, mainly due to restrictions on international travel. However, the strong service-based economy, high purchasing power of citizens, and institutional stability contributed to a relatively rapid return to forecasted levels, as illustrated in Figure 8.

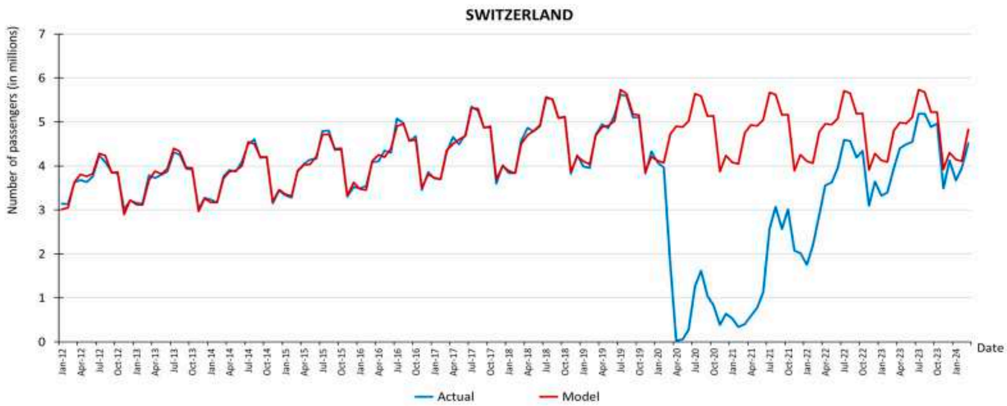


Figure 8. Comparison of model forecasts with the actual number of passengers in Switzerland.

As with the other developed models, the Shapiro–Wilk test was performed, yielding $W = 0.981$ and a *p-value* = 0.175. The *AIC* was 2509.1, indicating a complexity similar to that of the previously analyzed models. This model achieved an R^2 of 0.98738. Additionally, the *ME*, *MAE*, and *RMSE* values were calculated, confirming the high accuracy of the forecasts (Table 6).

Table 6. Assessment of forecast accuracy in the Holt-Winters model for the Swiss market.

Metric	Value
Mean Absolute Percentage Error (*MAPE*)	1.427%
Mean Error (*ME*)	−3299.916
Mean Absolute Error (*MAE*)	58,235.413
Root Mean Square Error (*RMSE*)	73,839.845

The Holt-Winters method proved effective in modeling passenger numbers on the selected aviation markets, achieving very low error values, as evidenced by *MAPE* below

2% in all cases. Moreover, across all countries the R^2 values exceeded 0.98, indicating a consistently high alignment between the fitted and observed series. Up to March 2020, the forecasts closely matched the actual data, after which significant and country-specific discrepancies emerged. The pandemic had a greater impact in countries with a higher share of international traffic (Portugal, Switzerland), while markets with a strong domestic network, such as Norway and Sweden, proved more resilient. Among the analyzed countries, Poland was positioned in the middle, combining a sharp decline with the forecasted growth potential. The models and results presented in this section form the basis for further analysis, including estimating losses, assessing the extent of recovery and pace of restoration of individual markets.

4.3. Robustness Check and Comparison of Alternative Models

To strengthen the empirical framework and verify the stability of the results, several additional forecasting approaches were estimated alongside the multiplicative Holt–Winters model. The aim of this part of the research was to assess whether the long-term projections used in the study are sensitive to the choice of forecasting method, or whether similar patterns emerge when applying alternative models. For this purpose, four commonly used approaches were considered:

- seasonal ARIMA model (SARIMA);
- basic structural model (BSM);
- trend–seasonal linear model (TSLM);
- Random Forest model (RF).

All models were trained on the same pre-pandemic period and evaluated using identical forecast accuracy metrics to ensure full comparability (Table 7).

Table 7. Forecast accuracy metrics for the examined models.

Model	MAE	RMSE	MAPE
Multiplicative Holt-Winters (HW)	1,952,926	2,407,673	1711.7
Seasonal ARIMA (SARIMA)	2,024,236	2,371,277	1652.3
Trend–seasonal linear model (TSLM)	2,058,869	2,370,695	1630.5
Random Forest model (RF)	1,101,460	1,498,198	1368.9
Basic structural model (BSM)	1,546,193	1,810,148	1210.2

It should be noted that the *MAPE* values obtained for the benchmark models are relatively high. This results from the fact that, during the pandemic collapse, actual passenger numbers fell to very low levels, which significantly inflates percentage errors. Similar behavior of *MAPE* in periods with near-zero observations is well documented in forecasting research [69–71]. For this reason, the comparison focuses on the relative differences between the models rather than on the absolute size of the *MAPE* values.

The benchmarking results indicate that some alternative models, particularly BSM and Random Forest, achieved lower error values. However, the objective of the comparison was not to select the single most accurate algorithm, but to verify whether the general behavior of the examined markets remains consistent across different forecasting techniques. In this respect, the Holt–Winters method offers several practical advantages: it provides a clear decomposition of trend and seasonality, can be applied consistently across all analyzed markets without extensive model-specific adjustments, and generates stable long-term forecasts suitable for comparative analysis.

Overall, despite differences in accuracy metrics, all models produced highly consistent qualitative patterns, both in terms of the magnitude of the COVID-19 impact and the overall pattern of recovery observed across air passenger transport markets. This confirms that the key findings of the study are robust and do not depend on the specific forecasting method applied. As a result, Holt–Winters remains the primary analytical model in this study, while the benchmarking results are reported to ensure methodological transparency and to support confidence in the results.

4.4. Comparative Analysis of Losses and Recovery of Markets

The final stage of the study involved analyzing and interpreting the results obtained from the developed models to assess and compare the condition of selected aviation markets disrupted by the epidemic-driven crisis. Forecasts generated using the Holt-Winters method were used to determine both the losses in the number of carried passengers (L_m) and the extent of their recovery (R_m) across successive time intervals (m) following the outbreak of the COVID-19 pandemic. The results indicate significant variation among the analyzed markets.

In the initial period, covering the first three months of the crisis, passenger losses ranged from 7.82 million in Sweden to 13.54 million in Portugal. Poland, with a figure of 10.91 million, fell in the intermediate group between Norway (8.22 million) and Switzerland (12.64 million). This differentiation persisted in subsequent time intervals, with the fastest accumulation of losses observed in Portugal and Switzerland, while lower losses occurred in Sweden and Norway. One year after the outbreak, cumulative losses exceeded 30 million passengers in all countries, with the highest recorded in Portugal (53.87 million) and Switzerland (48.45 million). Poland, at 44.45 million, was slightly below this group, while Sweden and Norway reached 30.84 million and 32.88 million, respectively. These findings indicate that markets more dependent on international travel and tourism experienced a greater passenger deficit relative to projected demand, primarily due to prevailing restrictions (e.g., entry requirements, health regulations) and the resulting decline in societal mobility. Conversely, the Scandinavian countries, with a significant share of domestic travel and an extensive internal network, were less affected by the crisis. The reduced sensitivity of these markets to international passenger flow restrictions translated into lower losses and positively influenced the initial phase of passenger traffic recovery.

Equally important from the perspective of market health are the observations regarding the extent of loss recovery (R_m). After three months, Norway recorded the highest extent of recovery at 18.83%, while Poland reached 10.16%. After six months, Norway maintained its lead (21.16%), whereas Poland and Switzerland showed similar values of around 15–16%. For Portugal and Sweden, despite Portugal experiencing a larger passenger deficit—13.6 million more than Sweden—the difference in extent of recovery remained below two percentage points (14.85% and 12.82%). One year after the pandemic outbreak, the R_m indicator remained relatively low across all countries (13.9% to 20.6%), reflecting the persistent demand barrier caused by mobility restrictions. A clear acceleration became visible only in the second year: between the 18th and 24th month, all markets recorded an increase of around 7 pp. Two years after the outbreak, the Norwegian market demonstrated the highest capacity for loss recovery. Poland, despite a delayed start, achieved the largest overall increase—from 10.16% to 27.11% (+16.95 pp.). This confirms the Polish market's ability to effectively compensate for lost volume, supported by deferred demand and restored airport throughput. Portugal and Switzerland, despite experiencing the highest losses and having substantial market potential, did not translate seasonal rebounds into higher extent of recovery, reaching only 26.62% and 27.01%, respectively. Sweden, despite a relatively low passenger deficit (52.94 million), exhibited the weakest extent of recovery, reaching 24.59% after two years. The contrast with Norway, whose losses were only about 6 million higher, but extent of recovery reached 29.34%, illustrates how markets with similar traffic profiles may follow different recovery dynamics. In Sweden's case, this likely reflects a more gradual demand response and weaker seasonal rebounds compared to Norway.

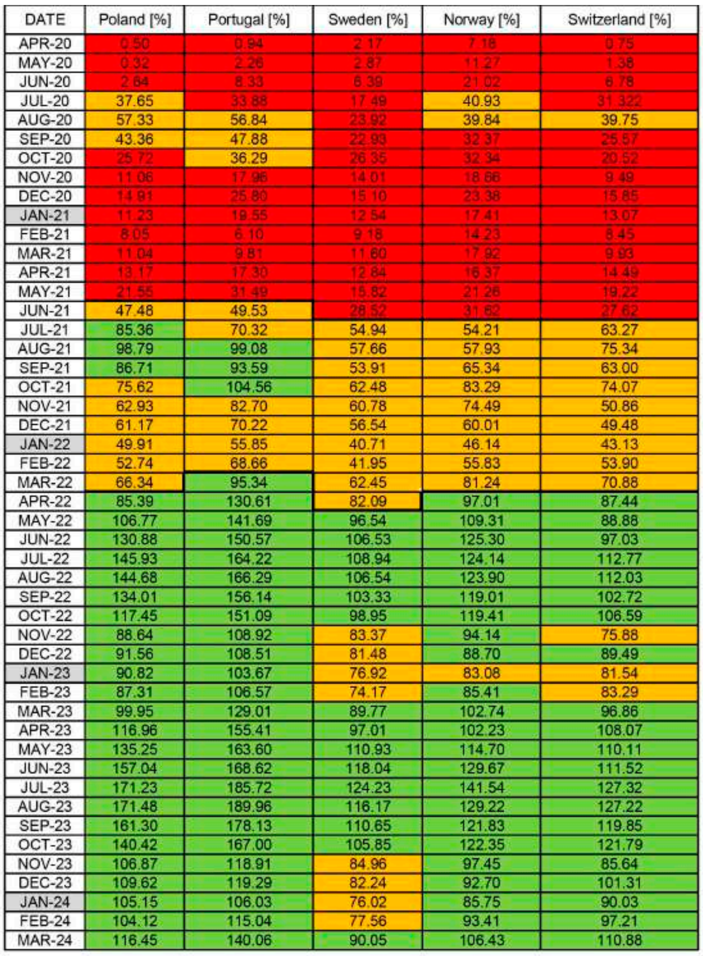
A summary of passenger losses and recovery levels across the analyzed markets is presented in Table 8.

Table 8. Crisis-related losses based on predicted values obtained by models.

Country	Period After COVID-19 Pandemic Outbreak									
	3 Months (m = 3)		6 Months (m = 6)		12 Months (m = 12)		18 Months (m = 18)		24 Months (m = 24)	
	L_m *	R_m [%]	L_m *	R_m [%]	L_m *	R_m [%]	L_m *	R_m [%]	L_m *	R_m [%]
Poland	10.907	10.16	24.433	15.25	44.45	15.42	66.77	20.38	79.84	27.11
Portugal	13.535	12.54	30.532	14.85	53.87	16.34	84.50	19.18	100.07	26.62
Sweden	7.819	14.34	16.933	12.82	30.84	13.86	45.03	17.34	52.94	24.59
Norway	8.218	18.83	17.534	21.16	32.88	20.56	50.09	21.83	59.03	29.34
Switzerland	12.639	12.93	25.725	16.41	48.45	15.43	70.83	19.72	83.86	27.01

* millions of carried passengers.

Next, the actual passenger transport results in the months following the outbreak of the COVID-19 pandemic were compared with data from January 2020 (*JAN-2020 = 100%*), which allowed for the assessment of the pace of restoration of passenger air transport markets in the selected European countries. The results obtained in this way were further visualized by assigning appropriate colors to the percentage values (*Dz*), as shown in Figure 9.



DATE	Poland [%]	Portugal [%]	Sweden [%]	Norway [%]	Switzerland [%]
APR-20	0.50	0.94	2.17	7.18	0.75
MAY-20	0.32	2.26	2.87	11.27	1.38
JUN-20	2.64	8.33	6.39	21.02	6.78
JUL-20	37.65	33.88	17.49	40.93	31.322
AUG-20	57.33	56.84	23.92	39.84	39.75
SEP-20	43.36	47.88	22.93	32.37	25.57
OCT-20	25.72	36.29	26.35	32.34	20.52
NOV-20	11.06	17.96	14.01	18.66	9.49
DEC-20	14.91	25.80	15.10	23.38	15.85
JAN-21	11.23	19.55	12.54	17.41	13.07
FEB-21	8.05	6.10	9.18	14.23	8.45
MAR-21	11.04	9.81	11.60	17.92	9.93
APR-21	13.17	17.30	12.84	16.37	14.49
MAY-21	21.55	31.49	15.82	21.26	19.22
JUN-21	47.48	49.53	28.52	31.62	27.62
JUL-21	85.36	70.32	54.94	54.21	63.27
AUG-21	98.79	99.08	57.66	57.93	75.34
SEP-21	86.71	93.59	53.91	65.34	63.00
OCT-21	75.62	104.56	62.48	83.29	74.07
NOV-21	62.93	82.70	60.78	74.49	50.86
DEC-21	61.17	70.22	56.54	60.01	49.48
JAN-22	49.91	55.85	40.71	46.14	43.13
FEB-22	52.74	68.66	41.95	55.83	53.90
MAR-22	66.34	95.34	62.45	81.24	70.88
APR-22	85.39	130.61	82.09	97.01	87.44
MAY-22	106.77	141.69	96.54	109.31	88.88
JUN-22	130.88	150.57	106.53	125.30	97.03
JUL-22	145.93	164.22	108.94	124.14	112.77
AUG-22	144.68	166.29	106.54	123.90	112.03
SEP-22	134.01	156.14	103.33	119.01	102.72
OCT-22	117.45	151.09	98.95	119.41	106.59
NOV-22	88.64	108.92	83.37	94.14	75.88
DEC-22	91.56	108.51	81.48	88.70	89.49
JAN-23	90.82	103.67	76.92	83.08	81.54
FEB-23	87.31	106.57	74.17	85.41	83.29
MAR-23	99.95	129.01	89.77	102.74	96.86
APR-23	116.96	155.41	97.01	102.23	108.07
MAY-23	135.25	163.60	110.93	114.70	110.11
JUN-23	157.04	168.62	118.04	129.67	111.52
JUL-23	171.23	185.72	124.23	141.54	127.32
AUG-23	171.48	189.96	116.17	129.22	127.22
SEP-23	161.30	178.13	110.65	121.83	119.85
OCT-23	140.42	167.00	105.85	122.35	121.79
NOV-23	106.87	118.91	84.96	97.45	85.64
DEC-23	109.62	119.29	82.24	92.70	101.31
JAN-24	105.15	106.03	76.02	85.75	90.03
FEB-24	104.12	115.04	77.56	93.41	97.21
MAR-24	116.45	140.06	90.05	106.43	110.88

Figure 9. Comparison of the pace of restoration of selected passenger air transport markets, visualized using color mapping.

As shown in Figure 9, all the analyzed air transport markets experienced a similar cycle, encompassing a sharp collapse, partial restoration, and then a return to stability near pre-pandemic levels, taking January 2020 passenger traffic as the baseline. The differences that emerged were mainly related to the intensity of the process and typically amounted to shifts of 1–2 months between individual phases, confirming that each European country was equally exposed to the unprecedented crisis in passenger aviation caused by the COVID-19 pandemic. It is worth noting that Poland, in many periods, achieved results comparable to—or even higher than—other economically stronger countries. At the same time, these developments took place within a sector that is also being shaped by longer-term climate-policy and decarbonization efforts.

The initial collapse in spring 2020 affected all countries, with passenger air traffic almost completely halted. In April 2020, the *Dz* index stood at only 0.5% in Poland, 0.75% in Switzerland, and 0.94% in Portugal, while conditions were slightly better in the Scandinavian markets. In the subsequent months of 2020, a partial restoration occurred, particularly in August, when Poland and Portugal reached approximately 57% of the pre-pandemic reference level, while Norway and Sweden remained below 40% and Switzerland below 30%. This was the first indication of the Polish market's strong responsiveness to seasonal restoration of air traffic. The following year, 2021, was marked by high volatility and clear differences between countries. In July, Poland reached over 85%, and in August nearly 99% of January 2020 traffic levels, indicating an almost full summer restoration. For comparison, Portugal recorded 70–99%, Switzerland 63–75%, and Norway and Sweden 54–58%. This confirms that Poland belonged to the markets with particularly high restoration levels, surpassing even the Scandinavian countries and Switzerland. During the winter of 2021–2022, all markets again fell to 40–70%, following a similar pattern. In 2022, the restoration process intensified. By May, the Polish market had exceeded the 100% threshold (106.77%), and in July and August reached around 145%. In the same months, the highest values were observed in Portugal (142–166%), while Norway recorded 109–125%, Sweden 97–109%, and Switzerland 89–113%. Thus, 2022 demonstrated that Poland was among the countries with the strongest restoration dynamics, matching markets supported by strong domestic traffic or high tourism potential. Results for 2023 and Q1 2024 reflect the stabilization of European passenger aviation. Poland maintained values above 105% for most months, frequently exceeding 150% (June–September 2023). The situation was even more favorable in Portugal, where the *Dz* index repeatedly surpassed 110%, often exceeding 160% (May–October 2023). During this period, Norway generally ranged between 90 and 130%, Sweden stabilized at 85–120%, and Switzerland remained within 95–127%.

The cross-country differences in the observed market dynamics after the pandemic outbreak can be partly explained by structural characteristics of the analyzed air transport systems. Norway and Sweden benefited from extensive domestic networks, which helped stabilize passenger volumes during periods of strict international travel restrictions. In contrast, Portugal and Switzerland were more exposed to international and tourism-driven demand, resulting in deeper initial declines and a slower return to pre-pandemic levels. Poland occupies an intermediate position: although domestic traffic plays a smaller role than in Scandinavia, this market combines diversified leisure, visiting-friends-and-relatives (VFR) and business demand with a strong presence of low-cost carriers. Taken together, these structural characteristics help account for the comparatively rapid improvement of the Polish market once pandemic-related travel restrictions were eased.

Considering all the obtained results, it can be concluded that the Polish passenger air transport market occupies a strong position within Europe and in recent years has clearly asserted its growing role in the region. A performance similar to that of economically stronger markets in the post-COVID-19 period demonstrates not only the flexibility of demand but also the effectiveness of measures undertaken by transport organizers, carriers, and airports. The epidemic crisis at the time proved to be critically impactful for passenger aviation, yet it simultaneously showed that Poland not only met the challenges but also joined the group of countries that managed to restore their transport capacity within a short period. At the same time, this experience highlights the need to strengthen the sector's resilience by developing recommendations and solutions that will enable effective responses to similar threats in the future.

A comparison of the five chosen markets indicates that the ways in which they reconstructed their passenger volume were closely associated with short-term crisis conditions such as the stabilizing effect of extensive domestic networks in Norway and Sweden or the relatively rapid reinstatement of leisure- and VFR-oriented capacity in Poland. In turn, longer-term structural characteristics, including the strong reliance on international traffic in Portugal and Switzerland, were more important for explaining both the extent of loss recovery and the pace at which markets restored pre-pandemic traffic levels. These observations help contextualize the practical recommendations.

Given the resilience patterns observed across all analyzed markets, several practical directions for policymakers and the aviation sector emerge from the comparative results:

- strengthening domestic and regional connectivity, which contributed to a faster pace of restoration in markets with more diversified demand structures;
- enhancing the operational flexibility of airlines and airports, allowing for rapid adjustments to sudden fluctuations in traffic volumes;
- maintaining adequate airport capacity reserves and intermodal accessibility, which facilitate a quicker scaling-up of operations once mobility restrictions are eased;
- developing clear and coordinated crisis-management procedures, helping stabilize connectivity during periods of severe disruption.

5. Conclusions

The COVID-19 pandemic significantly affected the functioning of passenger aviation, initially causing sharp declines in carried passenger volumes and subsequently forcing the process of market recovery. The publication assessed the condition of passenger air transport in Poland relative to selected European countries in the context of disruptions caused by the pandemic, using the Holt–Winters method to forecast passenger transport outcomes. The conducted study not only enabled the identification of the scale of incurred losses and the determination of the extent of their recovery based on forecasts obtained from the models but also allowed for the assessment of the pace of restoration in individual markets. The results showed that Poland, like other European countries, experienced a severe collapse in passenger air traffic during the initial phase of the pandemic. At the same time, however, the extent of loss recovery and the pace of market restoration in the following years proved comparable to those observed in stronger European economies. All markets included in the study recorded a significant deficit in the number of handled passengers during the first months of the pandemic, with the largest declines observed in Portugal and Switzerland—countries more dependent on international and tourism-related traffic. In contrast, the Scandinavian markets, characterized by a high share of domestic flights, demonstrated greater stability and returned to the growth path more quickly. Poland ranked in the middle of the comparison, with a passenger deficit of approximately 44.5 million after the first year of the pandemic. Nevertheless, the analysis of loss recovery showed that despite an initially delayed response, the Polish market achieved the highest increase in the R_m indicator across all cases (+16.95 pp), confirming its capacity to compensate for the lost volume in the medium term. Moreover, the assessment of the pace of restoration revealed that Poland, in many periods, achieved results comparable to—and sometimes exceeding—those of other countries. Since spring 2023, similarly to Portugal, Poland has not only fully restored its January 2020 passenger transport level but has also exceeded it for several consecutive months, which constitutes a highly positive signal for the condition of the Polish passenger aviation sector in the post-pandemic context. In summary, it can be concluded that Poland's role within the European air transport system continues to strengthen. These post-pandemic developments in passenger air transport should also be perceived in the context of a wider structural shift in the aviation sector, where long-term climate policy and decarbonization processes are gradually redefining the conditions under which European air transport develops. At the same time, this study—based on the challenging experience of the COVID-19 pandemic—clearly suggests that, beyond the growing passenger volume, equal importance should be placed on enhancing market resilience through coordinated actions of policymakers and operators aimed at shaping transport policies to prepare for future crises of a similar nature.

The contribution of the study can be summarized in several areas. First, the analysis applies the same forecasting approach to a group of European aviation markets that differ in size and structure, which allows long-term changes in passenger traffic to be examined in a comparable manner. Second, the use of pre-pandemic trend and seasonal patterns makes it possible to estimate the scale of passenger losses caused by COVID-19 and to assess both the extent of recovery and the pace of market restoration. Third, the comparison of markets shows that recovery trajectories are shaped not only by the depth of the initial decline but also by structural characteristics, such as market orientation or the role of domestic traffic. In this respect, the study extends previous work that has usually focused on individual markets or shorter time horizons.

From a practical perspective, this study provides valuable insights for infrastructure development planning, transport strategy formulation, and the strengthening of passenger aviation resilience to future crises. Above all, the results confirm the growing importance of Poland as a transport hub in Europe, which has significant implications for the continued development of infrastructure and the operational policy of the national carrier. In the longer term, one of the key factors that could help consolidate this position is the implementation of the Central Communication Port (CPK) project. The construction of CPK may overcome existing infrastructural constraints that limit the number of air operations and, consequently, the overall transport performance. By increasing capacity and improving connectivity, this investment could substantially enhance market competitiveness and stimulate further growth in passenger transport, thereby strengthening the aviation sector as well as related industries. Secondly, the analysis highlighted that market resilience depends not only on its scale but also on its structure. It demonstrated that a higher share of domestic flights can reduce vulnerability to global epidemic-related disruptions. Furthermore, the study emphasizes the need to develop comprehensive crisis management strategies, including diversification of route networks, implementation of epidemic risk management procedures, and a stronger role of the state in ensuring the stability of the air transport market.

The study has several limitations. The applied Holt–Winters method made it possible to develop highly accurate models that very effectively capture the trends and seasonality present in time series. However, it should be noted that the proposed models are based solely on historical data on the number of passengers carried, omitting significant economic and social variables such as air ticket prices, GDP level, or unemployment rate.

At the same time, the modeling framework does not explicitly incorporate broader socioeconomic determinants, such as income dynamics, labor market stability, the stringency of mobility restrictions or ticket price evolution, which may substantially shape both the depth of pandemic-related losses and the rate of recovery. Their inclusion in future research would enable a more multidimensional explanation of cross-country differences and deepen the analytical interpretation of resilience patterns. They also do not account for extraordinary factors such as armed conflicts, economic crises, or changes in tourist preferences, which could significantly influence passenger behavior and transport demand. Moreover, although the study compares Poland with a group of four other European markets, this set does not fully represent the diversity of pandemic impacts observed across the continent. While the chosen countries provide a structurally varied set of reference cases that differ in their domestic traffic shares, international orientations and long-term demand drivers, several other types of European aviation systems may nevertheless have experienced distinct post-pandemic dynamics—for example, those characterized by substantially different traffic scales, pronounced tourism-driven seasonality or very small national markets. As a result, the conclusions drawn in this study should be generalized with caution to countries whose scale or structural characteristics fall outside the range represented here. Additional markets were not included because only a limited number of European countries met all methodological requirements, namely full availability and internal consistency of data, comparable passenger volumes in the years immediately preceding the COVID-19 pandemic, and the ability to represent distinct aviation system configurations. Overall, these limitations do not undermine the credibility of the present results but rather define the scope and applicability of the study's conclusions.

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Abbreviations

The following abbreviations are used in this manuscript:

AIC	Akaike Information Criterion
ARIMAX	Autoregressive Integrated Moving Average with Exogenous variables
BSM	Basic Structural Model
BSTS	Bayesian Structural Time Series
CO_2	Carbon Dioxide
DWT	Discrete Wavelet Transform
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EU	European Union
ETS	Emissions Trading System
GDP	Gross Domestic Product
IATA	International Air Transport Association
LightGBM	Light Gradient Boosting Machine
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ME	Mean Error

MLP	Multilayer Perceptron
PLL LOT	LOT Polish Airlines
PM	Poisson Model
QPM	Quasi-Poisson Model
RF	Random Forest
RMSE	Root Mean Square Error
SARIMA	Seasonal Autoregressive Integrated Moving Average
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SAS	Scandinavian Airlines
SAF	Sustainable Aviation Fuels
SHAP	SHapley Additive exPlanations
SWISS	Swiss International Air Lines AG
TAP	Transportes Aéreos Portugueses
TSLM	Trend–Seasonal Linear Model
USA	United States of America
VFR	Visiting-friends-and-relatives

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Passenger traffic in Polish seaports in the face of the COVID-19 pandemic

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JEL Classification: C30, C52, C53, L91, R41

Abstract

The outbreak of the COVID-19 pandemic had a profound impact on the global economy and disrupted daily life across many regions of the world. Restrictions imposed at the time, such as the closure of national borders and restrictions on mobility, led to unprecedented challenges for the transportation sector and related tourism services compared with any prior crisis. This disruption also affected maritime passenger transport in Poland. This article aims to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that could support management in the event of future epidemic threats. Three different models are proposed, which showed that the epidemic crisis resulted in a significant decline in passenger traffic at Polish seaports. The most accurate proved to be the SARIMA model. The Holt-Winters model also demonstrated high fitting and predictive performance. In turn, the STL model offered intriguing insights with its time series decomposition, enabling a detailed analysis of individual components. A comparative analysis of the proposed models confirms their usefulness in forecasting passenger traffic in seaports in the face of disruptions such as the COVID-19 pandemic. These models can be an effective decision-support tool, helping to reduce the negative effects of future epidemic threats.

Introduction

Threats such as pandemics, geopolitical conflicts, climate change, and terrorist attacks significantly influence the modern world and global economy. The COVID-19 pandemic outbreak in 2020, for example, dramatically and unexpectedly affected social and economic systems, causing widespread destabilization across nearly all sectors (Clemente-Suárez, 2021). Maritime transport, essential for global passenger and cargo movement, was also impacted by the coronavirus. In response to the global epidemic crisis, shipping lines and operators had to adjust their operations to fit a new reality (Chua et al., 2022). Strict restrictions and health guidelines were imposed to curb the spreading of the virus and enhance public safety. Governments enforced widespread lockdowns and mandated social distancing and personal protective measures. Travel became more challenging due to temporary border closures, increased border checks, and mandatory quarantines upon entry into countries (Sobczuk, 2024). These restrictions, along with evolving legal regulations and new safety standards, affected the operational performance and transport outcomes. In the face of a dynamically changing situation, passenger maritime transport in Poland has faced the challenge of adapting to restrictions and new operating standards. The lack of appropriate analyses may make it difficult to understand the real scale of the problem and limit the sector's adaptive capacity, especially from the perspective of a potential recurrence of similar events. Therefore, this study aims to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that can support management in the event of future epidemic threats. This study not only showed the scale of disruptions caused by COVID-19 in passenger traffic in Polish seaports but, above all, provides effective forecasting tools for the maritime transport sector, which can be used for operational and strategic planning in the face of potential epidemic threats. This will enable a more effective response to similar challenges in the future, which will consequently reduce the negative effects of crisis events such as pandemics.

Literature review

In recent years, maritime transport in Poland has seen consistent growth. Port facilities have been modernized, and infrastructure has been expanded and enhanced through modern technologies. These investments aimed to increase cargo volumes and improve passenger comfort. As a result, the importance of maritime transport grew, leading to an increase in both passenger numbers and cargo volumes (Bocheński et al., 2021). However, this positive trend was disrupted by the outbreak of the COVID-19 pandemic in 2020. The pandemic led to a decrease in demand for transport services, port closures, and extended waiting times for port operations (such as docking and cargo handling) due to expanded security checks. Business and corporate travel were either postponed or replaced by virtual meetings for safety reasons. Tourists, constrained by mobility restrictions in most countries, opted for domestic travel, often using personal transportation. This shift was evident in transport statistics, particularly for summer cruises. The pandemic also led to rising freight and charter rates in container transport. Additionally, decreased demand for and prices of oil resulted in reduced deliveries, necessitating the storage of oil on floating tankers. These disruptions contributed to rising insolvencies and even bankruptcies among maritime carriers (Cullinane & Haralambides, 2021; Węcel et al., 2024).

Numerous publications have examined maritime transport during the COVID-19 pandemic. These studies analyze the operational activities of carriers and assess the measures taken to mitigate the negative impacts of reduced revenues from passenger transport and ferry services (Urbanyi-Popiolek, 2020). Another study explored the crisis's implications for the future of European maritime transport and proposes directions for further development (van Tatenhove, 2021). There have also been analyses of the impact of the pandemic on cargo maritime transport based on vessel types and the evaluations of cargo throughput in ports (Borucka & Kozlowski, 2023). Additionally, the need to reconfigure global supply chains managed by container transport and enhance their resilience through new digital solutions has been emphasized (Grzelakowski, 2022). The system of maritime navigation, with a focus on passenger traffic and trends within the European Union, has also been studied (Gracan, 2022). Some studies have visualized the impact of the COVID-19 pandemic on maritime transport in Poland and developed long-term forecasts for passenger traffic (Barczak, 2023). Nevertheless, there is a noticeable lack of focus on mathematical models that can evaluate and forecast passenger traffic in Polish seaports amid the pandemic's disruptions, which is the primary focus of this publication.

Materials and methods

This study utilized quarterly data on the passenger numbers to and from Polish seaports from 2004 to 2024, provided by Eurostat, to construct the time series necessary for the analysis (Eurostat, 2024).

Time series models were employed to identify and forecast temporal changes, allowing for the description of the process under study, the detection of the deterministic components, and the representation of the process as a function containing components such as the trend, seasonal variations, cyclical fluctuations, and random variations (Borucka & Guzanek, 2022; Bouboulas et al., 2022; Oszczypala et al., 2023). By identifying these components and the internal dynamics of the time series, future values of the time series can be forecast (Rodrigues et al., 2022; Kozlowski et al., 2023). Three different models were applied in this study, and their results were compared (Liu et al., 2024). If observations of the lagged series appear as dependent variables in the model, it is appropriate to apply autoregressive processes AR (p). If the variables in the model are a combination of lagged external disturbances, moving average models are suitable MA (q). Often, combining these two models – i.e., ARMA (p,q) – is the most effective approach.

However, for non-stationary series that can be transformed into a stationary form (through differencing), it is appropriate to use ARIMA (p,d,q) models. When seasonal components are also included in the model, the SARIMA (p,d,q)(P,D,Q)[S] model is obtained (Riaz et al., 2023), i.e.,

$$\begin{aligned}&\left(1-\varphi_1 B-\varphi_2 B^2-\cdots-\varphi_p B^p\right)\cdot\\&\cdot\left(1-\Phi_1 B^s-\Phi_2 B^{2s}-\cdots-\Phi_P B^{Ps}\right)\cdot\\&\cdot\left(1-B\right)^d\left(1-B^s\right)^D y_t=\\&=\left(1+\theta_1 B+\theta_2 B^2+\cdots+\theta_q B^q\right)\cdot\\&\cdot\left(1+\Theta_1 B^s+\Theta_2 B^{2s}+\cdots\Theta_Q B^{Qs}\right)\varepsilon_t\end{aligned} \tag{1}$$

where $\varphi_1,\varphi_2,\ldots,\varphi_p$ is the autoregression coefficients, $\Phi_1,\Phi_2,\ldots,\Phi_P$ is the seasonal autoregression coefficients, $\theta_1,\theta_2,\ldots,\theta_q$ is the moving average coefficients, $\Theta_1,\Theta_2,\ldots,\Theta_q$ is the seasonal coefficients of the moving average, B is the differentiation operator $B_{yt} = y_t - y_{t-1}$, and ε_t is the random error at time t.

The Holt-Winters model, which is applicable to time series with trend, seasonal, and random fluctuations, was also used. There are two variants of this model that differ in the nature of the seasonal components. The additive model is preferred when seasonal variations are roughly constant across the series, while the multiplicative model is used when seasonal variations change proportionally with the series level (Koehler et al., 2001; Ribeiro et al., 2019). This study used a multiplicative model consisting of the forecasting equation Y^*_{t+m} and three smoothing equations – i.e., the level L_t, trend B_t, and seasonality S_t – which are expressed as

$$Y^*_{t+m}=\frac{L_t+B_t\cdot m}{S_{t-s+m}} \tag{2}$$

$$L_t=\alpha\frac{Y_t}{S_{t-s}}+\left(1-\alpha\right)\left(L_{t-1}+B_{t-1}\right) \tag{3}$$

$$B_t=\beta\left(L_t-L_{t-1}\right)+\left(1-\beta\right)B_{t-1} \tag{4}$$

$$S_t=\gamma\frac{Y_t}{L_t}+\left(1-\gamma\right)S_{t-s} \tag{5}$$

respectively, where α, β, and γ are the exponential smoothing coefficients such that α, β, $\gamma \varepsilon$ (0;1), Y_t is the actual value at time t, S is the length of the seasonality cycle (for quarterly data, L = 4), and m is the forecast horizon (Wang, 2019).

The last model employed was the seasonal-trend decomposition using LOESS (STL), which decomposes the time series to analyze each component separately. As a result, the value of the variable under study (Y_t) at time t is expressed as the sum of the trend, seasonal, and remainder so that:

$$Y_t = M_t + S_t + R_t \tag{6}$$

where M_t is the trend at time t, S_t is the seasonality at time t, and R_t is the remainder component at time t.

The component values are determined through a series of locally weighted regression (LOESS) smoothing procedures, which are based on fitting a weighted polynomial regression to the observation time (Dagum & Luati, 2003). The time series is iteratively adjusted until the trend and seasonality stabilize using a multi-step process involving alternating moving averages and LOESS smoothing. The seasonal, trend, and remainder components are then extracted using the following equations:

$$S_t=S_t^{(k+1)} \tag{7}$$

$$M_t=M_t^{(k+1)} \tag{8}$$

$$R_t = Y_t - S_t - M_t \tag{9}$$

respectively, where k is the number of iterations for the respective steps.

A model selection was based on the Akaike information criterion (AIC) and the Bayesian information criterion (BIC), which are calculated using the following formulae:

$$\text{AIC} = 2\,k - 2\ln(L) \tag{10}$$

$$\text{BIC} = k\ln(n) - 2\ln(L) \tag{11}$$

where k is the number of parameters in the model, L is the reliability function, and n is the number of observations. Lower AIC and BIC values indicate a better model fit.

For each of the models used, the accuracy of the determined forecasts was also evaluated. Forecast accuracy for each model was assessed by calculating the mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) via:

$$\text{MAE}=\frac{1}{n}\sum_{t=1}^{n}\left|Y_t^*-Y_t\right| \tag{12}$$

$$\text{MSE}=\sum_{t=1}^{n}\frac{\left(Y_t^*-Y_t\right)^2}{n} \tag{13}$$

$$\text{RMSE}=\sqrt{\text{MSE}}=\sqrt{\sum_{t=1}^{n}\frac{\left(Y_t^*-Y_t\right)^2}{n}} \tag{14}$$

where Y_t^* is the forecasted value at time t, Y_t is the actual value at time t, and n is the number of observations. Lower error values indicate higher forecast accuracy and, thus, better predictive performance of the model (Saigal & Mehrotra, 2012).

In this paper, time series analyses and the development of all the mathematical models were performed using R Core software (version 4.3.3) with packages that provide a set of algorithms for data preprocessing and time series forecasting (R Core Team, 2024).

Comparison of the mathematical models describing passenger traffic in Polish seaports

This study began with an analysis of the passenger numbers in Polish seaports using basic descriptive statistics. Data from each quarter of 2004–2023 were analyzed and displayed using a box plot, as shown in Figure 1.

Transport data from 2004–2023 were also analyzed by quarter (Q1–Q4), as illustrated in Figure 2.

The plots reveal significant variability in the passenger numbers from year to year, especially compared to 2019. Notably, 2020–2021 show distinct outliers, which are attributed to the disruptions caused by the COVID-19 pandemic, which led to temporary mobility restrictions, including maritime travel (Chua et al., 2022; Węcel et al., 2024).

Additionally, the data exhibit quarterly seasonality, with the highest passenger numbers in the third (Q3) and second (Q2) quarters. This pattern is due to favorable weather conditions for maritime travel during the spring and summer months, leading to increased cruise bookings. The third quarter's

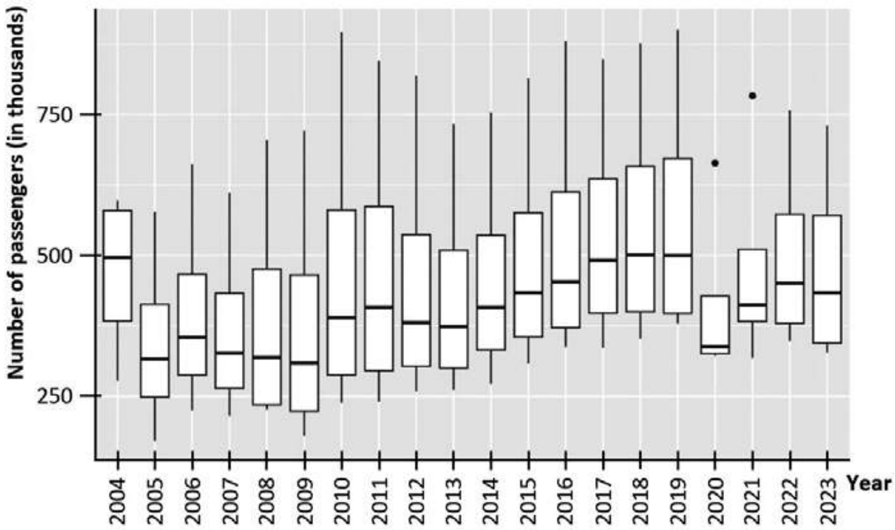

Figure 1. Box plot of the passenger numbers in Polish seaports from 2004 to 2023 (based on Eurostat, 2024)

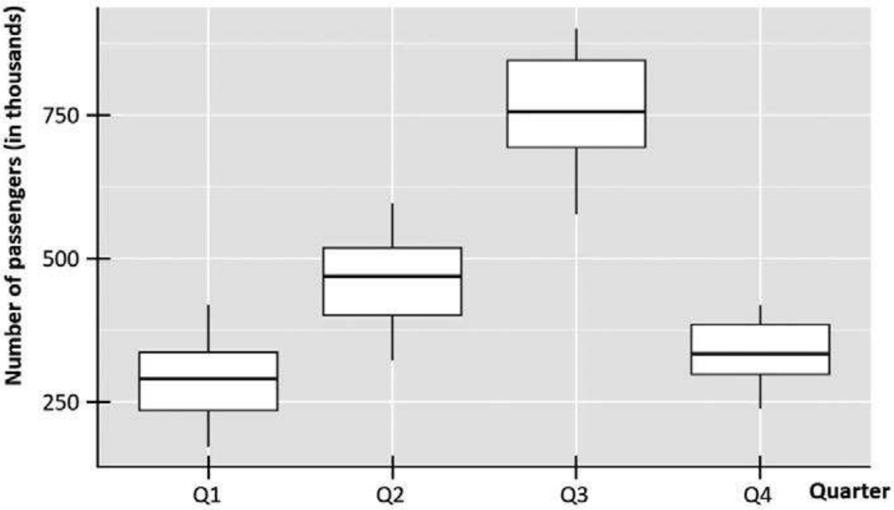

Figure 2. Box plot of the number of passengers in Polish seaports by quarter based on data from 2004 to 2023 (based on Eurostat, 2024)

holiday season also significantly contributes to increased passenger traffic in seaports. In the remaining parts of the year (Q1 and Q4), there are fewer passengers, primarily due to business travel and less frequent tourist trips (Gracan et al., 2022; Barczak, 2023).

Next, a time series analysis of the quarterly passenger numbers from 2004–2023 was conducted. The dataset was divided into training and testing sets, with the division occurring at the end (Q4) of 2022, as shown in Figure 3.

The SARIMA model was initially proposed. The best model, determined based on information criteria, was SARIMA (1,0,0)(0,1,1)[4]. The estimated parameter values for this model are presented in Table 1.

Table 1. SARIMA (1,0,0)(0,1,1)[4] model parameters

Model parameters		
Coefficients	AR 1	SMA 1
	0.6488	−0.3189
Standard error	0.1009	0.1432

The values of the individual information criteria (i.e., AIC and BIC) are similar and are summarized together in Table 2.

Table 2. Evaluation of SARIMA (1,0,0)(0,1,1)[4] model fit

Evaluation of the model fit	
Aikike information criterion (AIC)	791.71
Bayesian information criterion (BIC)	798.54

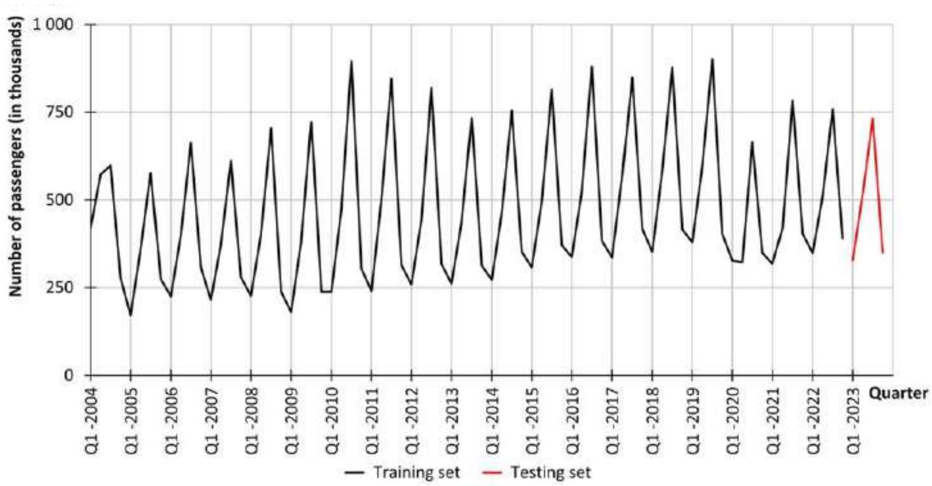

Figure 3. Dataset division into training and testing sets (based on Eurostat, 2024)

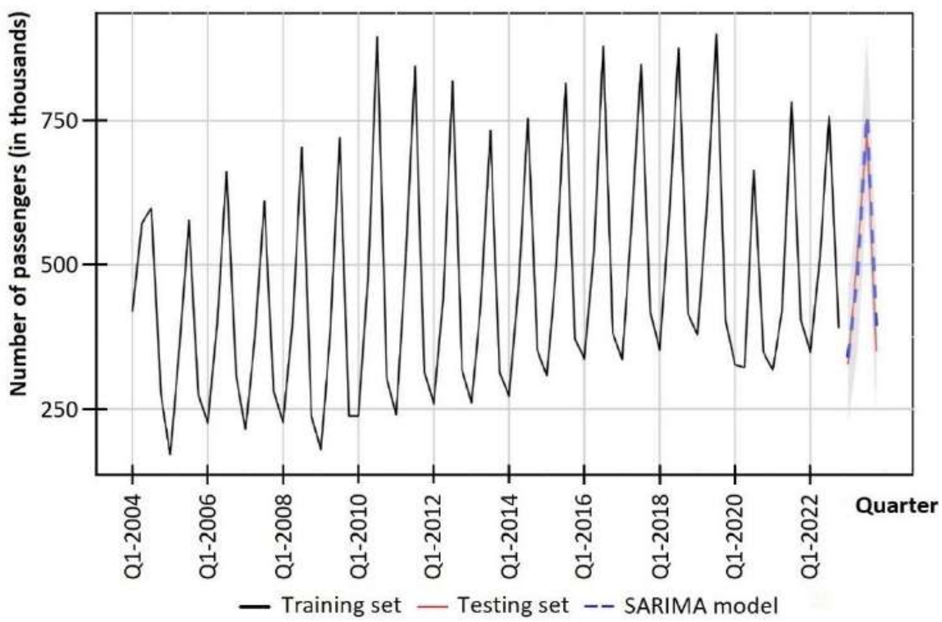

Figure 4. Passenger numbers in Polish seaports with SARIMA (1,0,0)(0,1,1)[4] model forecast

The MAE, RMSE, and MSE forecast errors were also determined. The results were satisfactory, with lower errors for the testing set, indicating high prediction accuracy (Table 3).

Table 3. Forecast accuracy measures for the SARIMA (1,0,0)(0,1,1)[4] model

Forecast accuracy measures		
	Training set	Testing set
MAE	36.6301	29.6084
RMSE	54.8371	31.6947
MSE	3007.1097	1004.554

The actual passenger numbers in Polish seaports from 2004–2023, along with the forecast based on the SARIMA (1,0,0)(0,1,1)[4] model, are shown in Figure 4.

The next proposed model was the Holt-Winters model with multiplicative seasonality. The values of the smoothing parameters and initial parameters are presented in Table 4.

Table 4. Parameters of the multiplicative Holt-Winters model

Model parameters			
Smoothing parameters		Initial parameters	
Alpha (α)	0.3655	l	550.1898
Beta (β)	0.0001	b	0.2276
			1.3228
Gamma (γ)	0.6344	s	1.1652
			0.8699

The Holt-Winters model was also evaluated using information criteria (Table 5). The values obtained were higher than those for the SARIMA model, indicating a poorer fit than the SARIMA (1,0,0)(0,1,1)[4] model.

Table 5. Evaluation of the multiplicative Holt-Winters model fit

Evaluation of the model fit	
Aikike information criterion (AIC)	951.47
Bayesian information criterion (BIC)	972.45

Forecast errors for the Holt-Winters model were also determined (Table 6). The error values were satisfactory for both the training and test datasets. Moreover, for the testing set, the MAE and RMSE errors were lower than those for the SARIMA model, indicating that the forecasts from this model have smaller prediction errors.

Table 6. Forecast accuracy measures for the multiplicative Holt-Winters model

Forecast accuracy measures		
	Training set	Testing set
MAE	38.7481	29.1471
RMSE	56.0513	27.0655
MSE	3141.7505	849.5518

The actual passenger numbers in Polish seaports from 2004 to 2023, with the 2023 forecast from the multiplicative Holt-Winters model, are shown in Figure 5.

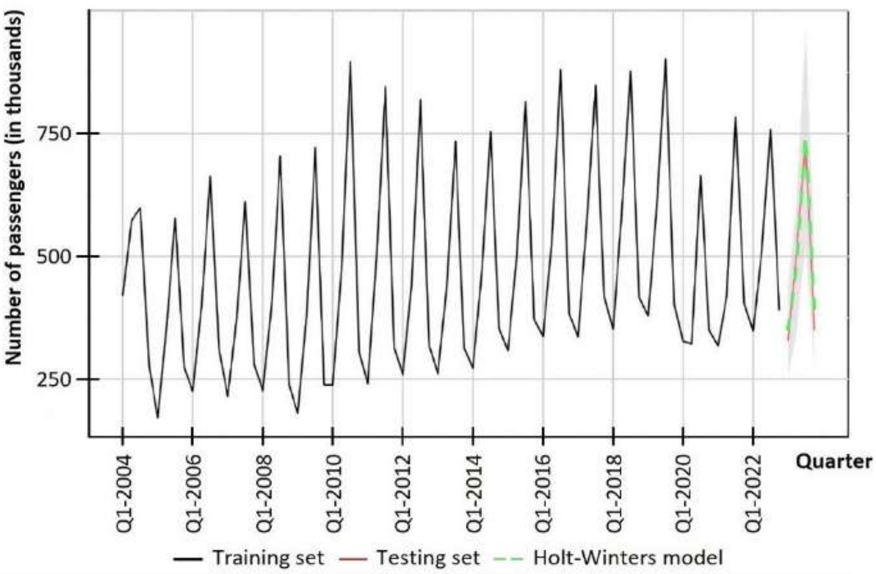

Figure 5. Passenger numbers in Polish seaports with the multiplicative Holt-Winters model forecast

The last model proposed is seasonal-trend decomposition using LOESS (STL), which allows for the decomposition of the time series into seasonal, trend, and remainder components. The STL model components and interquartile range (IQR) calculations are presented in Table 7.

Table 7. STL model components with IQR calculations

Timeseries components			
	Seasonal	Trend	Remainder
Min.	−178.3537	342.6228	−143.8509
1st Qu.	−137.745	397.6869	−18.0134
Median	−60.7633	463.6279	−0.3256
Mean	0.00001	461.5133	−0.6449
3rd Qu.	76.9817	507.9549	19.9074
Max.	299.8803	582.0477	110.5635
Inter-quartile range calculations (IQR)			
STL seasonal	STL Trend	STL remainder	Data
214.73	110.27	37.92	274
78.4%	40.2%	13.8%	100.0%

As before, the forecast errors were also determined for the STL model, the values of which indicate high prediction accuracy (Table 8).

Table 8. Forecast accuracy measures for the STL model

Forecast accuracy measures	
MAE	28.8357
RMSE	37.1778
MSE	1382.186

The decomposition of the analyzed time series (Figure 6) reveals certain regularities within its components. Most notably, throughout the entire period, quarterly seasonality remains consistent, unaffected by global events such as the COVID-19 pandemic. However, when discussing disruptions, the trend line, as determined by the STL model, highlights the significant impact that the spread of the SARS-CoV-2 virus had on societal mobility, particularly on maritime passenger transport.

Analyzing the trend in passenger numbers from Q3 in 2019 to Q3 in 2020, a significant decline is evident, attributable to the epidemic crisis during that period. Therefore, considering both the seasonal component and the overall trend, it can be concluded that the COVID-19 pandemic outbreak had a substantial impact on transport outcomes, reducing passenger traffic at Polish seaports. However, it did not disrupt the established pattern of seasonal interest in cruises across different quarters.

The actual passenger numbers in Polish seaports from 2004 to 2023, along with the forecast generated using the STL model, are presented in Figure 7.

The last phase of this study involved comparing the results obtained by each of the mathematical models under consideration. Actual values were compared with forecasts for the individual quarters of 2023. The higher forecasted values, compared with the actual figures (except for Q2 2023), were obtained across all the models, which confirm that the SARS-CoV-2 pandemic significantly disrupted passenger traffic (Table 9). All the proposed models were also compared graphically with the testing set (Figure 8).

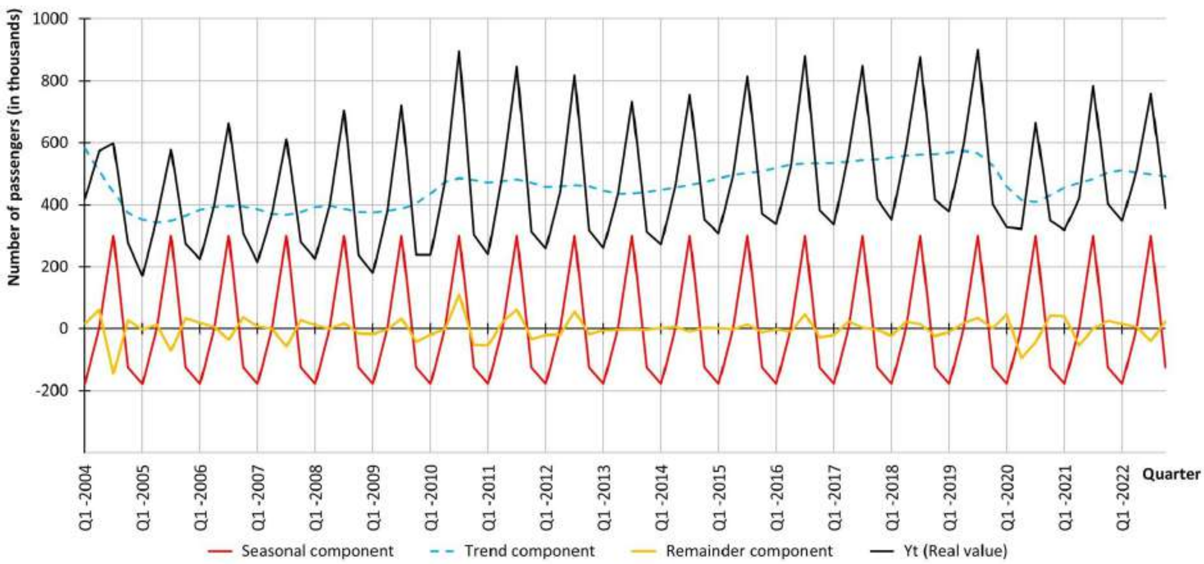

Figure 6. Decomposition of the time series of passenger numbers in Polish seaports using the STL model

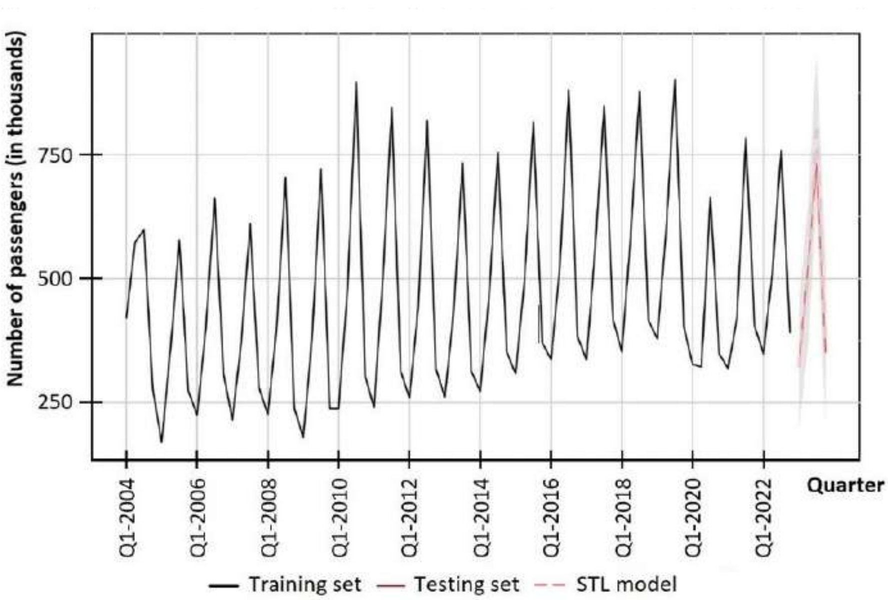

Figure 7. Passenger numbers in Polish seaports with the STL model forecast

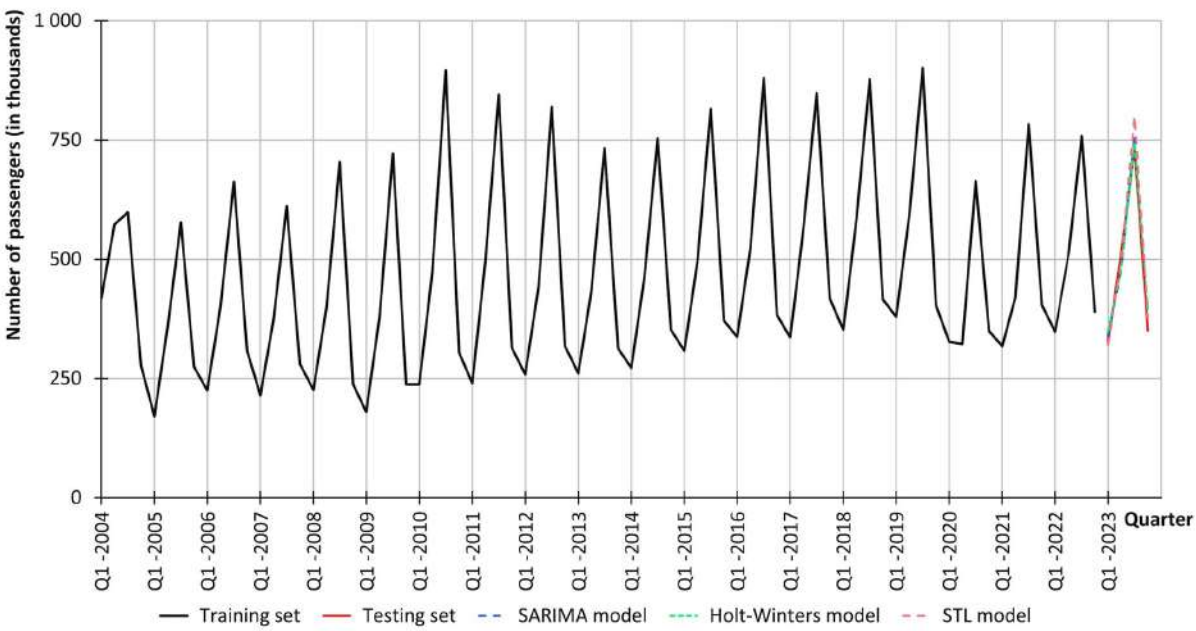

Figure 8. Comparison of mathematical models for passenger numbers in Polish seaports

Table 9. Comparison of forecasts obtained by individual mathematical models

	Q1-2023	Q2-2023	Q3-2023	Q4-2023
Actual value	328.00	517.00	731.00	350.00
SAIRMA model	339.23	479.71	760.60	390.32
Holt-Winters model	348.66	483.61	744.20	391.02
STL model	320.77	501.81	799.00	374.92

The results indicate that the SARIMA model provided forecasts closest to the actual values. Satisfactory results were also achieved with the multiplicative Holt-Winters model, while the STL model showed the lowest accuracy, particularly for the forecast of Q3 in 2023. Nevertheless, each proposed model offers valuable and effective tools for forecasting passenger traffic in Polish seaports, even amid global disruptions such as the COVID-19 pandemic.

Conclusions

The impact of the COVID-19 pandemic on maritime transport was evident globally. In passenger transport, the disruptions were primarily linked to restrictions imposed, including those regarding mobility, resulting in a decrease in cruise passengers. The aim of this study, which was to assess the impact of the COVID-19 pandemic on passenger traffic in Polish seaports and to develop mathematical models that could support management in the event of future epidemic threats, has been achieved. This publication provides an evaluation of passenger traffic in Polish ports as a case study. For this purpose, mathematical models that accounted for both seasonality and trends in the time series were employed and then compared. The study confirmed that the epidemic crisis led to a marked decline in passenger traffic at Polish seaports. The forecasts produced were generally higher than the actual figures, highlighting the disruptions caused by the pandemic. This finding is reinforced by the comparison of the results obtained by three different mathematical models. Based on the values of the information criteria and the comparison of actual data with the forecasts, the SARIMA model proved to be the most accurate. The Holt-Winters model also demonstrated high fitting and predictive performance. The STL model offered intriguing insights as well, with its time series decomposition enabling a detailed analysis of individual components in light of the disruptions caused by the pandemic. In summary, the comparative analysis of the proposed models (i.e., SARIMA, Holt-Winters, and STL) has shown their usefulness in forecasting changes in the number of passengers in Polish seaports in the face of disruptions such as the COVID-19 pandemic. These models can be an effective decision-making support tool, helping to limit the negative effects of future epidemic threats. Conclusions based on these models can be used to develop strategies in the event of a recurrence of similar challenges.

However, despite the obtained results, the study has several limitations. First of all, the analysis was based on data concerning Polish seaports only, which may limit the universality of the proposed models and the possibility of generalizing conclusions for other countries. Another limitation is the lack of an in-depth qualitative analysis, which could complement the analyzed quantitative results by better understanding the factors determining the variability in passenger traffic. It is also worth noting that the study focused on the relatively short-term effects of the pandemic, which may ignore long-term changes in passenger behavior and preferences. An additional limitation of the study was the availability of only quarterly data, which may translate into the predictive performance of the proposed models and, therefore, may not reflect changes occurring in the months following the outbreak of the pandemic. Hence, it may not take into account the full scope of external influences, such as global economic changes or current initiatives related to crisis management.

Taking into account the obtained results, further research should focus primarily on extending the analyses to other countries or regions in order to understand global trends and their local diversity. This would also allow for an assessment of the universality of the developed forecasting models in terms of their application to other transport markets. Another direction of research may be to consider more advanced models using, among others, machine learning algorithms and analyses based on Big Data sets. This would make it possible to consider additional factors, which in turn would improve the performance of the models and the precision of the forecasts. Such studies should include a detailed analysis of the impact of external factors, including state policy and sanitary regulations. Another important direction of the research is to prepare recommendations and proposals for solutions aimed at increasing the safety of the Polish maritime transport sector in the event of similar events in the future. The authors plan to conduct more detailed analyses in this area in future studies.

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Application of Selected Mathematical Models for Analysis and Evaluation of the Functioning of Transport Processes in Crisis Situations

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Abstract:

Purpose: *This article aimed to identify the possibilities of using mathematical modeling to analyze and evaluate the functioning of transport processes in crisis situations. The study responds to the need for analytical approaches that enhance transport management under disruptions caused by economic, environmental, health, social, and military crises.*
Design/Methodology/Approach: *The study is based on a classification of crisis types and a systematic overview of mathematical modeling methods that can be applied to the analysis and evaluation of transport processes. It combines theoretical and empirical approaches, drawing on data from international statistical sources, public agencies, and national transport authorities. The models were applied to several case studies, including public transport in Warsaw, seaport passenger traffic following the COVID-19 outbreak, road safety analysis and the assessment of transport–energy–emission relationships in Poland.*
Findings: *The analysis's results indicate that mathematical models can be used as valuable tools for analysing and evaluating the functioning of transport processes in specific crisis situations. Their application allows for the identification of disruptions, prediction of changes, and assessment of relations between selected indicators. Classical statistical and econometric models make it possible to identify structural changes and long-term dependencies, while machine learning models demonstrate particular strength in detecting complex interrelations and predicting risk patterns. The results show that the proper selection of mathematical models, depending on the type of crisis, data availability, and the nature of the analysed process, supports decision-making in transport and contributes to improving the safety, sustainability and shaping a resilience of transport systems, which is especially significant in the context of potential crises.*
Practical Implications: *The study's results provide a solid basis for applying mathematical modeling methods in the analysis and assessment of transport processes under crisis conditions. The findings can support policymakers, public institutions and transport authorities in identifying potential disruptions, forecasting their effects, and planning response strategies as well as strengthening overall resilience. They also indicate that the proper use of modeling tools facilitates informed decision-making and contributes to improving the safety*

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and stability of the transport sector in challenging and dynamic environments.
Originality/Value: *Previous studies have focused mainly on the impacts of individual crises or the use of single modeling techniques. This research introduces an interdisciplinary and comprehensive approach that combines the typology of crisis situations with the classification and application of mathematical modeling methods with examples. It contributes to the development of a coherent analytical framework for modelling transport processes and supporting their functioning in the event of disruptions of diverse origin.*

Keywords: *Transport resilience, global crises impact, transportation, mathematical modelling, time series models, machine learning algorithms.*

JEL Code: *C51, C52, R41.*

Article Type: *Research article.*

1. Introduction

The introduction should identify key ideas of the research, why it is important, pose research question that needs to be answered and how the findings contribute to the discipline. Introduction includes the description of the study, problems, sets aim and tasks of the research, research methods applied, and presents novelty and topicality of the research as well as lists problematic questions of the conducted research, information sources, delimitations of research subjects, and theoretical discussion.

The modern world still has to deal with dynamic and often unpredictable phenomena, such as pandemics, armed conflicts and rapid social changes. These events have a significant impact on almost all areas of life, including transport. Therefore, research that allows for assessing the effects of disruptions, forecasting changes and potential threats, in order to identify areas requiring improvement in the transport sector, is becoming increasingly important.

There is a wide interest in the impact of crises on transport activities in the literature. In particular, the spread of the COVID-19 highlighted the susceptibility of transport to disruptions, which resulted in intensified research into the consequences of this type of events. In passenger transport, the pandemic has led to a substantial decrease in the number of travellers, changes in the structure of transport and forced the adaptation of services to more restrictive sanitary requirements (Gkiotsalitis and Cats, 2020; Burdzik, 2023).

In many urban areas around the world, serious mobility restrictions have been introduced and traveller preferences have changed (Galeazzi, Cinelli, Bonaccorsi, Pierri, Schmidt, Scala, Pammoli and Quattrociocchi, 2021; Świderski, Sobczuk and

Borucka, 2024). Freight transport has also experienced disruptions, including delays in supply chains and the need to adapt infrastructure and transport organisation to new conditions (Kukulski, Lewczuk, Góra and Wasiak, 2023).

In addition to health crises, researchers are also analysing the impact of economic, social and environmental disruptions on transport (Borca, Putz and Hofbauer, 2021; Rothengatter, 2011). Their effects are complex and multidimensional, which requires the use of analytical methods. In this area, mathematical models are used and constantly developed, allowing not only the description and interpretation of changes, but also the forecasting of further consequences.

The literature is dominated by regression, moving average and exponential smoothing models (Riaz, Sial, Sharif and Mehmood, 2023), as well as more complex tools (Oszczypała, Ziółkowski and Małachowski, 2023) – e.g., vector-autoregressive models (Borucka and Sobczuk, 2025a) or time series decomposition methods (e.g., STL) (Sobczuk and Borucka, 2025).

Machine learning algorithms such as Random Forest, KNN or CART are also increasingly used (Silva, Andrade and Ferreira, 2020). They are used both in research on road traffic safety (Borucka and Sobczuk, 2025b), as well as in forecasting the load on transport networks (Tsolaki, Vafeiadis, Nizamis, Ioannidis and Tzovaras, 2022) and in assessing the impact of GHG emissions (Yifan, Wu, Zhou, Wu, Yang, Wallington, Shen, Tan and Deng, 2022).

Despite the wide interest in the discussed topic, there is still a lack of studies that would comprehensively combine the typology and review of contemporary crisis events with the division of mathematical modeling methods and their practical application in research on the functioning of transport under disruption conditions. The recognition of this gap has guided the direction and objective of the current research.

The aim of article was to identify the possibilities of using mathematical modeling to analyze and evaluate the functioning of transport processes in crisis situations. This study is based on following principle research questions:

- How can specific crisis situations affect the functioning of transport?
- What mathematical models can be used to analyze and evaluate the functioning of transport processes in specific crisis situations?

In response to the above, the article characterizes and classifies crises and indicates the consequences of these events for the transport sector. The work continues with a description of mathematical approaches used in research on the impact of crisis situations on transport. Then, the possibilities of using selected mathematical models were presented, based on examples from recent years. This study provides a new perspective on the impact of crisis situations on transport by combining a review of crisis types with a classification of mathematical modeling methods and their practical application. The article includes both theoretical and empirical examples, showing specific tools that can be used in the analysis and assessment of disruptions to transport processes.

Thus, it contributes to the development of an interdisciplinary approach to transport management in crisis conditions.

2. Overview of Contemporary Crisis Situations

A crisis situation is defined as a situation that adversely affects the security of people, significant property, or the environment, thereby significantly limiting the operation of competent public administration bodies due to inadequate forces and resources (Government of Poland, 2007). Very often, an incident that is initially perceived as a crisis situation can escalate to a state of deeper disorder known as a crisis. According to one approach, a crisis results from unwanted events linked to natural, technological, or human causes (Farazmand, 2018).

Another source views a crisis as a situation in which core societal values such as safety, health, security, or economic stability are under threat (Rodríguez, Quarantelli and Dynes, 2007). Thus, the two terms remain closely linked and can be considered together as successive stages of the same process of disruption. In literature crises are classified in a variety of ways, with the most common approaches focusing on their genesis and areas they disrupt.

However, an unambiguous and fully objective classification is not possible. First of all, each case has unique characteristics and scale of impact. In addition, crisis situations often have multiple causes and effects that intertwine. This study uses a classification based on the approach presented in (Sobczuk and Borucka, 2024). The division of crises with characteristics and specific examples is presented in Table 1.

Table 1. *Adopted division of crises with examples*

Crisis type	Characteristics	Example
Economic	Marked by a sudden drop in market indicators and asset values, accompanied by rising unemployment and inflation. It also involves reduced production, lower investment and consumption, and widespread financial instability at both corporate and individual levels.	- Global financial crisis (2008); - Euro area crisis (2009).

Environmental	Involves significant deterioration of ecological systems and natural resources. It poses threats to public health due to factors such as climate change, atmospheric pollution, and environmental degradation. These crises are often linked to both anthropogenic influences and natural phenomena, and are observable through tangible environmental damage.	- Rising global temperatures; - Intensification of extreme weather phenomena; - Forest fires in Southern Europe (2024)
Health	Directly impacts public health through the rapid spread of disease, leading to increased demand for medical services. It requires implementation of preventive measures such as quarantine and personal protective equipment (PPE).	- Spread of the MERS virus (2012); - Western African Ebola epidemic (2013-2016); - COVID-19 pandemic (2020).
Social	Disrupts core societal frameworks, undermining collective identity and weakening social cohesion. It often results in diminished trust in actions of governmental institutions and public authorities, and can trigger widespread civil responses such as protests, strikes, or movements.	- European migrant crisis (2015); - Protests against rising food and energy prices in Europe; - High mortality rate in traffic accidents.
Military	Poses a direct threat to human life and safety through the deployment of military forces and the use of weapons. These crises result in physical destruction, including damage to critical infrastructure and essential services.	- Ukraine-Russia War (2022); - Iran-Israel tensions (2024).

Source: *Author's elaboration based on Sobczuk and Borucka, 2024.*

Subsequently, the characteristics of the listed types of crises were deepened with a comparative analysis in terms of their impact on transport functioning, which made it possible to better understand the nature and extent of the disruptions taking place in each case (Table 2).

Table 2. *Comparative analysis of different crises' impacts on transport functioning*

Crisis type	**Impact on transport**
Economic	Reduced travel demand driven by financial constraints; decline in freight volumes; increased reliance on public transport; decreased household spending on transport-related services.
Environmental	Limited availability of raw materials for vehicle manufacturing; increased demand for sustainable modes of transport; rising costs of traditional fuels
Health	Reduced use of public transport due to health concerns; lower interest in tourism-related travel; changes in transport mode preferences; restrictions on international mobility; disruptions in logistics and shifts in transported goods.

Social	Travel activity may decrease as a result of public anxiety over safety and societal unrest; difficulties in ensuring the safety of transport infrastructure; declining public confidence in traffic regulations; increasing societal pressure for infrastructural and legal reforms; disparities in access to transportation systems.
Military	Damage to transport systems and infrastructure; restricted access to air and maritime routes; suspension of cross-border transport; elevated risk of attacks on ongoing transport operations.

Source: *Author's elaboration based on Sobczuk and Borucka, 2024.*

As shown in Table 2, the different types of crises can have a significant but different impact on transport leading to numerous disruptions that, due to the role of transport in the functioning of the economy and society, also impinge on all other areas of life.

Given, that in recent years there have been many unfortunate events of various origins and effects, the occurrence of such risks in the future cannot be ruled out. It is therefore justified to use mathematical modeling methods to study the impact of crisis situations on transportation processes, through which, among other things, it is possible to assess the effects of disruptions or identify areas for improvement, and as a result, draw lessons for the future.

Considering the probability of further threats, it is important to develop and implement solutions or strategies based on an analytical approach.

This will increase the resilience of the transport sector in order to be able to fully cover the transport needs generated in crisis conditions, thus leading to maintaining the stability of the entire economy.

3. Research Methodology

The relationship between crisis situations and transportation functioning is bidirectional. This means that not only specific events can lead to disruptions of in transportation processes, but also transportation itself can be a factor intensifying crises, for example, through adverse effects on the environment.

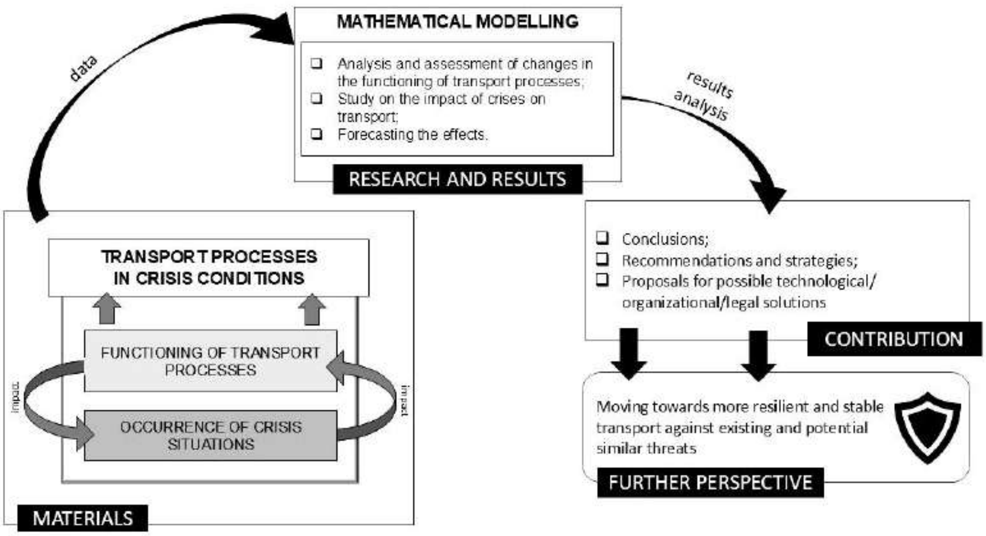
The interrelationships that occur can be analyzed on the basis of statistical data covering various aspects of transport operations - both directly related to transport and relating to economic issues, traffic safety or the state of the environment (including gas emissions, resource exploitation).

Among the sources used are data from international databases and agencies (including the World Bank, Eurostat, IEA), statistics from national public institutions (e.g., Statistics Poland), reports from services (e.g., Police Headquarters), studies of research centers (e.g., Motor Transport Institute) and information from transport operators (e.g., from municipal transportation authorities).

These data can be used in mathematical modeling, which – depending on the adopted research problem – constitutes the basis for identifying dependencies, analysing disruptions and forecasting changes in transport in crisis conditions. This enables the formulation of practical conclusions, including the identification of areas requiring improvement, which in turn can support decision-making processes in planning actions and strategies in disruption situations. This is particularly important in the context of the growing complexity and dynamics of contemporary threats.

The adopted methodology for research on transport processes in crisis situations based on mathematical modeling is presented in Figure 1.

Figure 1. *Adopted methodology for research on transport processes in crisis situations using mathematical modeling.*



Source: *Author's elaboration.*

This article identifies the possibilities of applying mathematical modeling to analyze and evaluate the functioning of transport processes in crisis situations by referring to specific research results (examples) that were achieved by following the methodology shown.

The adopted classification of selected mathematical modeling methods in the context of their use for research on transportation in threat conditions is presented in the next section.

4. Selected Methods of Mathematical Modeling of Transport Processes

Mathematical modeling involves using the language of mathematics, i.e. mathematical symbols and relations, to describe a specific fragment of reality. A correctly selected and constructed mathematical model for a given process allows it to be analyzed and useful conclusions to be drawn, which is especially important when disruptions are observed. In the study of transport processes in crisis situations, mathematical models can be classified into several groups depending on the analytical approach and possibilities.

Classical statistical models include a range of methods used in time series analysis, and their main purpose is to model and forecast changes over time based on historical data. Among the basic approaches is regression in time series. Regression modeling is used to determine the relationship between the quantities under consideration and to predict the values of some quantities based on the values of others.

The simplest variant is linear regression, which assumes that an increase in one variable is accompanied by an increase or decrease in another variable. Polynomial regression, on the other hand, makes it possible to model more complex, non-linear relationships by introducing higher orders of explanatory variables.

Among the classic statistical models, it is also important to point out exponential smoothing methods that allow to reduce the variance of a time series using a weighted moving average of past values, with weights decreasing exponentially with distance in time (Saigal and Mehrotra, 2012).

The most basic variant is a single exponential smoothing referred to as a Brown model and used for series that do not show a development trend, and fluctuations in values are due to random factors (Brown, 1962). The extension of this model is double exponential smoothing taking into account the linear trend (Holt model). In addition, in situations where the considered time series additionally show cyclical patterns, triple exponential smoothing (Holt-Winters model) is used, taking into account the smoothing parameter (α), trend (β) and seasonality (γ).

These models come in two varieties - additive or multiplicative, depending on the nature of the seasonal element (Riaz, Sial, Sharif and Mehmood, 2023; Holt, 1960). The most advanced class of classical statistical models are autoregressive and moving average models. If the explanatory variables in the model are time-lagged observations of the series, it is appropriate to use autoregressive processes AR*(p)*.

If the variables in the model are a combination of time-lagged external disturbances, moving average models MA*(q)* will be appropriate. In many cases, the most effective will be a combination of these two models - ARMA*(p, q)* (Sobaszek, Gola and Kozłowski, 2020).

However, for non-stationary series, but which can be transformed to a stationary form (using differencing), it is appropriate to use ARIMA*(p,d,q)* models. Additionally, if seasonal components are included, the SARIMA *(p, d, q) (P, D, Q) [S]* model is used (McDowall, McCleary and Bartos, 2019).

Another category is made up of econometric and multivariate models, which make it possible to study the interrelationships between multiple time variables, not only in economics, but also in transportation analyses. Among them, it is necessary to distinguish the vector autoregressive model (VAR), which extends classical autoregressive models to multidimensional cases, making it possible to analyze the interrelationships between many variables simultaneously (Lütkepohl, 2005).

When the considered variables exhibit non-stationarity, an error correction model (VECM) is used to model long-term relationships between variables, while eliminating errors due to short-term fluctuations. These models are particularly important in the study of time series cointegration (e.g., the Johansen cointegration test), that is the search for a relationship in which the variability of two or more time series is similar over the long term (Johansen, 1988).

It is also appropriate to distinguish a group of models used for decomposition of time series, which means their distribution into individual components, such as trend, seasonality, random component, which facilitates the identification of changes occurring in the processes under study.

Classical decomposition uses two approaches - additive, in which the sum of the components reproduces the values of the time series, and multiplicative, where the components are multiplied with respect to each other, which allows better representation of dynamic changes. Another approach is the X11 decomposition, which is based on the classical variant, but additionally uses moving average filters, often called X-11 type filters (Dagum and Bianconcini, 2016).

Still another type is LOESS decomposition. In this case, the values of the individual components are determined by a sequence of smoothing procedures using locally weighted regression (LOESS), which is based on fitting a weighted polynomial regression for a given observation time (Dagum and Luati, 2002).

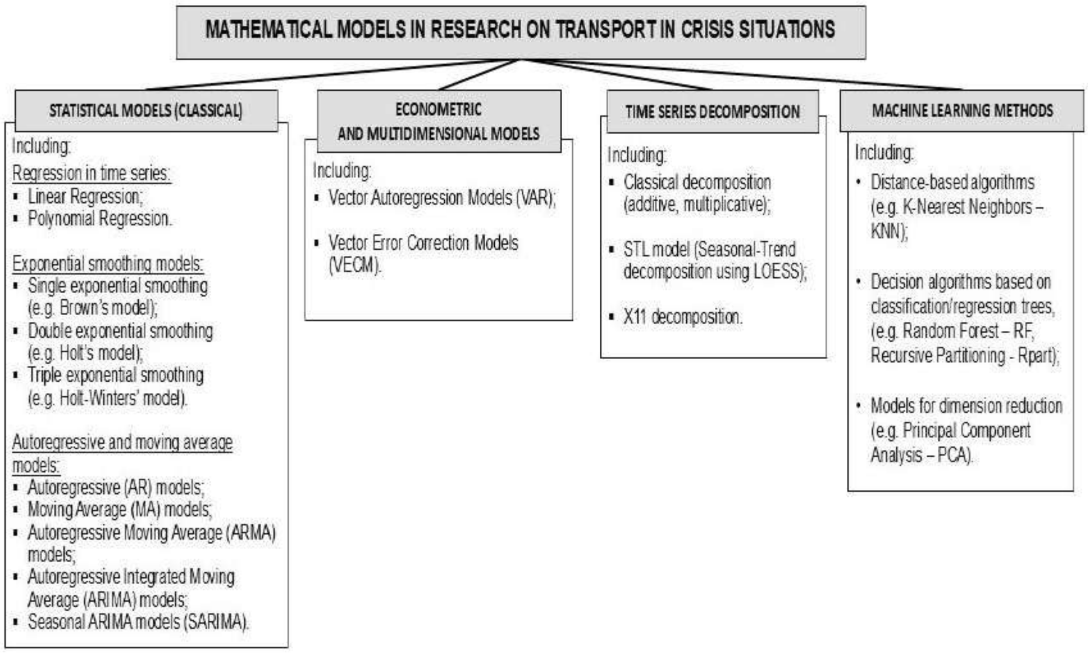
It is noteworthy that one of the constantly developing fields of artificial intelligence is machine learning, which also finds application in research involving the operation of transportation under emergency conditions (Izdebski, Michalska, Jacyna-Gołda and Gherman, 2024). Machine learning methods allow analysis of large and compound data sets, which traditional techniques are often unable to process effectively (Li, Song and Shi, 2024). These include distance-based algorithms such as K-Nearest Neighbors (KNN), which are based on the analysis of similarities between observations in feature space (Uddin, Haque, Lu, Moni and Gide, 2022).

Another class are algorithms based on decision trees applied to both classification and regression problems. These include Random Forest (RF), which involves constructing multiple decision trees at learning time and generating a class that is the dominant of the classes (classification) or the predicted mean (regression) of the individual trees (Moussa and Aoulmi, 2025).

Another example is Recursive Partitioning (RPart), which divides data into smaller groups (partitions) in such a way as to obtain the most homogeneous subgroups with respect to the objective variable (class in the case of classification) (Mahesh, 2020). Dimensionality reduction models such as Principal Component Analysis (PCA) can also be useful as they allow the transformation of the original set into a new set of uncorrelated variables (so-called principal components) (Illahi and Mir, 2021).

These components are linear combinations of the original variables, where each subsequent principal component explains as much of the variability in the data as possible. A classification of selected mathematical modeling methods applicable to the analysis and evaluation of the performance of transportation processes in emergency situations is shown in Figure 2.

Figure 2. *Mathematical models in research on transport in crisis situations.*



Source: *Author's elaboration.*

The mathematical approaches listed are widely applicable to research on the impact of crises on transportation allowing, among others, the analysis of data structures and properties of time series, identifying dependencies, assessing the level of disturbances and forecasting changes or consequences of events.

However, it is necessary to note that each method is based on different assumptions and provides different possibilities, so the selection of a model should take into account not only the specifics of the problem under study, but also the availability and quality of input data. Examples of the application of part among mentioned mathematical models in research of the functioning of transportation processes in crisis situations are shown in the next section of the publication.

5. Examples of Model Applications in Research on the Functioning of Transport Processes in Crisis Situations

5.1 Analysis of Changes in Urban Public Transport in the Context of Events from 2019-2022

In 2020, due to the outbreak of the COVID-19 pandemic, collective public transport experienced serious disruptions resulting from mobility restrictions and enforced sanitary and hygiene requirements. In addition, in February 2022, the Russian-Ukrainian conflict escalated and turned into a regular war.

This initiated the migration of the population towards the west, including Poland, which translated into changes in demand for passenger transport. These events became the starting point for examining the effects of crisis situations on operations in collective public transport in Warsaw (Świderski, Sobczuk and Borucka, 2024). The study considered data from 2019-2022, which was obtained from the statistics of the City of Warsaw and the Warsaw Public Transport Authority.

The article uses exponential smoothing models, i.e., Brown and Holt methods. The collected data was divided into three periods: pre-pandemic, COVID-19 pandemic and Ukraine-Russia war period, which were put through exponential smoothing. Then, the directions of change in each period were identified by determining a linear trend from the projected values.

This approach allowed to examine the dynamics of indicators describing the implementation of transport processes, such as the transport performance and the number of passengers carried, as well as to analyze changes in transport needs in terms of the number and structure of tickets sold.

The results indicate that health and military crises, and in this case the pandemic COVID-19 and the war in Ukraine, had an impact on the functioning of Warsaw's public transport, as confirmed by fluctuations in indicators describing the implementation of transport processes, as well as changes in the number and structure of tickets sold.

The analysis showed a decline in total ticket sales from 7.08 million in 2019 to 4.88 million in 2020, while the number of passengers decreased from 1201.5 million to 726.1 million (-39.56%) during the period. In 2022, due to the inflow of immigrants to Warsaw, there was an increase in demand for transportation and an improvement in the values of the analyzed indicators, which is reflected, among others, in the determined upward trend of transport work (100.1 thousand VKT per month).

In addition, each of the models obtained a high fitting with real data and satisfactory prediction accuracy (MAPE: 3.7-10.1%), which confirms their usefulness under the considered conditions.

From the perspective of applying mathematical modeling in transportation research under crisis conditions, the discussed study is an example of the use of classical quantitative methods to identify and assess the effects of collective public transport disruptions in a large urban agglomeration.

The Brown and Holt models presented in this case, due to their flexibility and low computational complexity, are applicable to the analysis of the implementation of transportation processes in the context of health and military crises, enabling rapid capture of structural changes, which can support both transportation providers and authorities. Overall, it has been shown that relatively simple statistical models, properly chosen to characteristics of the data, can provide information to assess the scale of change, identify breakthrough moments and support planning of responses to similar events in the future.

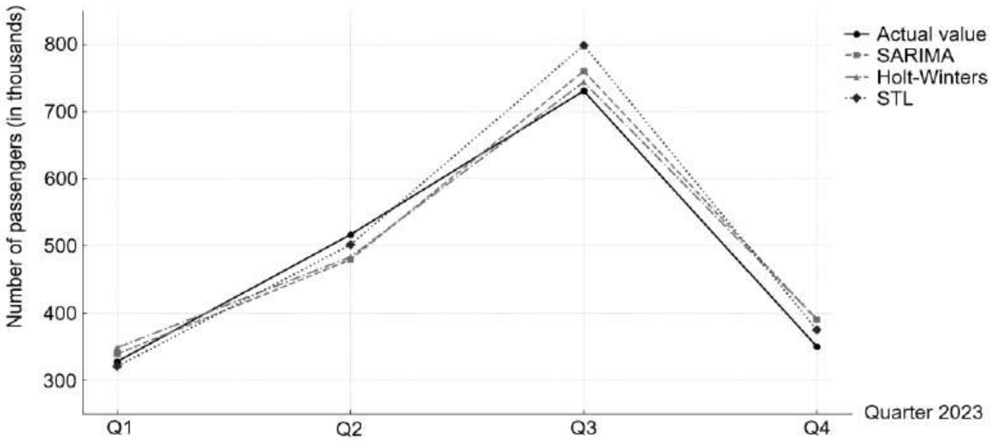
5.2 Study on COVID-19-Related Changes in Passenger Traffic at Seaports

An example of the use of mathematical modeling to analyze and evaluate the functioning of transportation processes in crisis situations is the study of passenger traffic disturbances at Polish seaports. In the article (Sobczuk and Borucka, 2025) the authors assessed disruptions caused by COVID-19 pandemic and developed models that could support management for similar threats in the future. Quarterly data covering the years 2004-2023 obtained from Eurostat were used.

Three different models were considered: SARIMA (1,0,0)(0,1,1)[4], the multiplicative Holt-Winters model and the STL decomposition. The input data was divided into a training set and a test set. The moment of division was the end of 2022 - data up to and including Q4-2022 were used for model estimation, while from Q1-2023 were allocated for verification and evaluation of predictive performance. Based on the value of the information criteria and the comparison of observations with predictions, both the SARIMA model and the Holt-Winters model proved to be very effective and comparable in terms of fit and accuracy.

These models reflected well the overall trends in the data and seasonal fluctuations, making them valid tools for forecasting passenger traffic at seaports. In turn, the use of STL decomposition allowed for a detailed examination of the time series components, providing deeper insight into the effects of disruptions caused by the pandemic. The model confirmed the stability of the seasonality despite the disruptions that occurred. It is noteworthy that in most quarters of 2023, the obtained forecasts exceeded the actual values, suggesting that passenger cruise demand has not returned to the levels that would have been expected in the absence of the pandemic (Figure 3).

Figure 3. *Comparison of model forecasts with actual number of passengers at seaports.*



Source: *Author's elaboration.*

The study demonstrates that mathematical models can provide information on how the transport sector responds to disruptions - in this case of epidemic origin. Despite the use of models with different structures, all showed a similar response to disrupted data. Identified discrepancies interpreted in the context of a crisis can act as an indicator of the level of disruption of a given process.

In addition, the decomposition method allowed the evaluation of seasonality patterns and the rate of return to previous values, which confirms the potential not only in forecasting, but also in in diagnosing the condition of the transport sector in crisis situations. In summary, the approach used in this study can support the identification of areas particularly susceptible to disruption and serve to assess the resilience of transportation, thereby supporting planning and operational activities in the face of potential, not only health crises.

5.3 Application of Machine Learning Models in Road Safety Research

Mathematical models based on machine learning (ML) are used in road safety research, enabling the identification of patterns and relationships between factors leading to road accidents, as well as the prediction of potential threats and their consequences. This has been shown, among others, on the example of Poland (Borucka and Sobczuk, 2025b).

The article identifies key factors influencing road safety, and ML models have been developed to identify road accidents and predict the severity of injuries for participants. The research used data from 2019–2023 collected by Polish Police within the Accident and Collision Register System (SEWiK), simultaneously processed and disseminated by the Motor Transport Institute.

In the first stage, the Random Forest algorithm, along with the mean decrease Gini index, was used to identify 11 key variables most strongly associated with road safety levels in Poland. Then, three different ML models were considered: K-Nearest Neighbors (KNN), Random Forest (RF) and Recursive Partitioning and Regression Trees (RPart). The data set was divided into training (85%) and test (15%), and then a cross-validation controller (10-fold cross-validation) was prepared. Similar results were obtained for all proposed models (Table 3).

***Table 3.** Comparison of evaluation parameters for the models considered*

Model	**Accuracy [%]**	**Kappa**	**Sensitivity [%]**			
			"no injuries"	**"minor injuries"**	**"severe injuries"**	**"deaths"**
KNN	64.2	0.4162	88.90	62.72	14.83	6.23
RF	63.02	0.414	84.95	59.03	24.90	12.17
RPart	62.86	0.3664	97.13	56.11	0	0

***Source:** Borucka and Sobczuk, 2025b.*

Among the considered models, Random Forest demonstrated the highest accuracy, particularly in identifying infrequent classes. For tasks where overall prediction accuracy is the central objective, KNN provided a balanced alternative.

In turn, the RPart model can be used as a fast baseline model, but needs improvements to cope with rare classes. In summary, all the models made it possible to determine the relationship between the characteristics of an event and its consequences.

The study presented should be considered in the context of the persistent and diffuse social crisis represented by traffic accidents. Statistics confirm that these incidents continue to result in a high number of injuries and fatalities, which in turn translates into significant costs for the state, a burden on the health care system and long-term social consequences, including a dramatic impact on the lives and material situation of the victims' families.

Used ML models have made it possible to identify factors contributing to the occurrence of injuries among participants and detect recurring patterns of risk.

These models, integrated with a unified system for collecting data on incidents and traffic flows, could serve as a decision-support tool for improving transportation infrastructure, planning preventive measures, and intervening at the local and national levels, including changes to existing regulations (such as speed limits).

The study shows that combining a modeling approach with road safety management can foster the formation of more resilient mobility systems, leading to real reductions in social and economic costs resulting from accidents.

5.4 Exploring the Link between Transport Energy Use, CO2 Emissions and Government Revenues

The Johansen cointegration method evaluates the cointegration of many time series and is based on the Vector Error Correction Model (VECM). For example, this approach has been employed to investigate the link between energy consumption in the transportation sector (TFECT), CO_2 emissions (CO_2T) and public revenues (GREV) in Poland (Borucka and Sobczuk, 2025a). The study covered data from 1990-2022 obtained from the International Energy Agency, the World Bank Group and the International Monetary Fund.

As a result of the stationarity tests (ADF, PP, KPSS), the first-order integration of the variables was confirmed, which allowed the Johansen cointegration method to be applied. This test showed the presence of two cointegration vectors (ect1, ect2), which enabled the estimation of the VECM model. Finally, based on the obtained coefficients, the long-run equilibrium equations were of the form:

$$TFECT - 34{,}483.64 \times GREV - 26{,}828.31 \times TREND = 0 \quad (1)$$

$$CO_2T - 2.467 \times GREV - 1.807 \times TREND = 0 \quad (2)$$

Moreover, after establishing cointegration relationships, an impulse response function (IRF) was applied to evaluate the dynamics between the time series and identify the main transmission channels.

The study proves that total final energy consumption in transportation (TFECT) is a major factor shaping both the level of CO_2 emissions from transportation (CO_2T) and the amount of government budget revenues (GREV).

Growth in TFECT leads to a significant, although time-distributed, increase in emissions and affects the level of budget revenues, especially through fuel taxes and fiscal burdens related to transportation activity. At the same time, it is shown, that the CO_2T time series responds to TFECT, but also to its own shocks, suggesting that CO_2 emissions are self-reinforcing.

Public revenue (GREV), while significantly related to transportation energy, shows less clear responses, indicating the indirect nature of this relationship. The results obtained confirm that all the analyzed variables are related to each other in the long term, although with different intensity and time dynamics. As a result, these identified relationships made it possible to identify specific policy implications and courses of action.

The importance of using mathematical modeling in the mentioned study should be considered in the context of growing economic and environmental tensions, particularly fiscal constraints, overexploitation of fossil fuels, rising energy costs and intensifying emission pressures in the transport sector. The results suggest that an integrated approach combining fiscal and environmental goals seems most appropriate, including such as taxing fuels based on emissions intensity, or redistributing revenues from transportation taxes for the development of more sustainable infrastructure.

The application of the VECM in the Johansen test framework enabled the identification of sustainable linkages between fiscal and environmental policies, which is particularly important in the context of leading the energy transition under conditions of limited financial resources. IRF analysis, in turn, provides additional information on the distribution of effects over time, which can support the planning of stepwise corrective actions. Overall, the study demonstrates that econometric and multidimensional models provide important support for formulating sustainable strategies, and therefore shaping the transport sector's resilience to economic and environmental crises.

6. Conclusions

The aim of article was to identify the possibilities of using mathematical modeling to analyze and evaluate the functioning of transport processes in crisis situations. Based on the classification of crisis types and overview of selected modeling approaches, it was shown that statistical, multidimensional and econometric models, as well as time series decomposition methods and machine learning algorithms, can be valuable tools to conduct the study of transport disruptions caused by health, social, military, economic or environmental crises. Analysis of selected models based on event cases from recent years confirmed that:

- Crisis situations have a clear, measurable impact on the functioning of transport by primarily affecting demand, structure, safety and organization;
- Appropriate selected mathematical models can identify disruptions, forecast changes and support decision-making processes in transportation planning and management;
- Simple statistical models are operationally useful, while advanced econometric and ML methods offer deeper strategic insights.

The conducted study provides not only a theoretical ordering of models and classification of crises, but also indicates directions for the practical use of methods depending on the defined problem, the specifics of the threat and the characteristics of the input data. This makes it possible to consider the analysis not only as a closed scheme, but as a flexible approach to support the development of interdisciplinary transport management and a starting point for shaping its resilience to potential disruptions.

Several existing limitations must also be pointed out. First of all, the effectiveness of the presented models depends to a large extent on the availability and quality of data, the acquisition of which in crisis situations can pose serious difficulties. Besides, all the analyzed models were based only on available historical data and specific types of crises, according to the adopted classification, which on the one hand sets the framework for application, but also suggests a direction to be extended and deepening.

In view of the results, future research should focus on integrating quantitative models with solutions based on streaming data, Big Data and artificial intelligence. AI, combined with machine learning, anomaly detection and automatic optimization, can support the analysis of disruptions with hard-to-define patterns, making it particularly valuable for complex or sudden crises. This is forward-looking in the context of building resilient, scalable and predictive transportation systems capable of real-time response, which could prove crucial in the face of future crises of difficult-to-evaluate genesis, nature and scale.

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