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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).

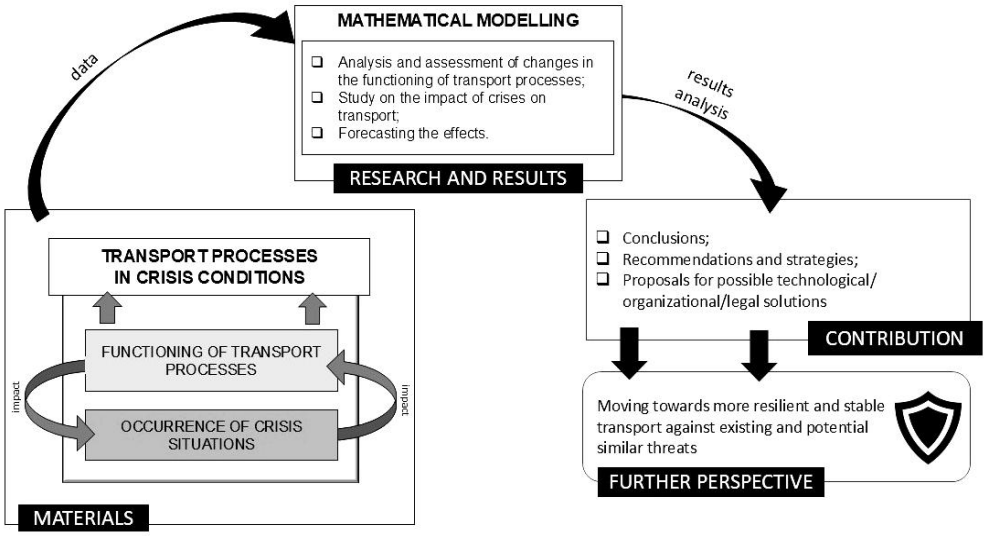
Among the sources used are data from international databases and agencies (including the World Bank, Eurostat, IEA), statistics from national public institutions (e.g., Statistics Poland), reports from services (e.g., Police Headquarters), studies of research centers (e.g., Motor Transport Institute)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

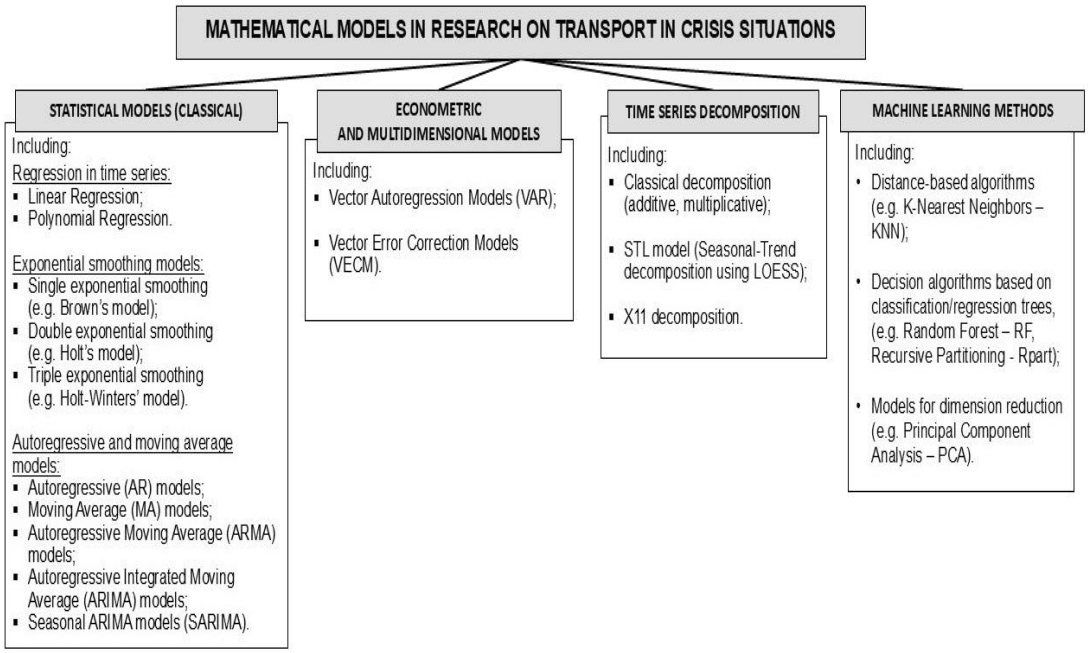
It is noteworthy that one of the constantly developing fields of artificial intelligence is machine learning, which also finds application in research involving the operation of transportation under emergency conditions (Izdebski, Michalska, Jacyna-Gołda and Gherman, 2024). Machine learning methods allow 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

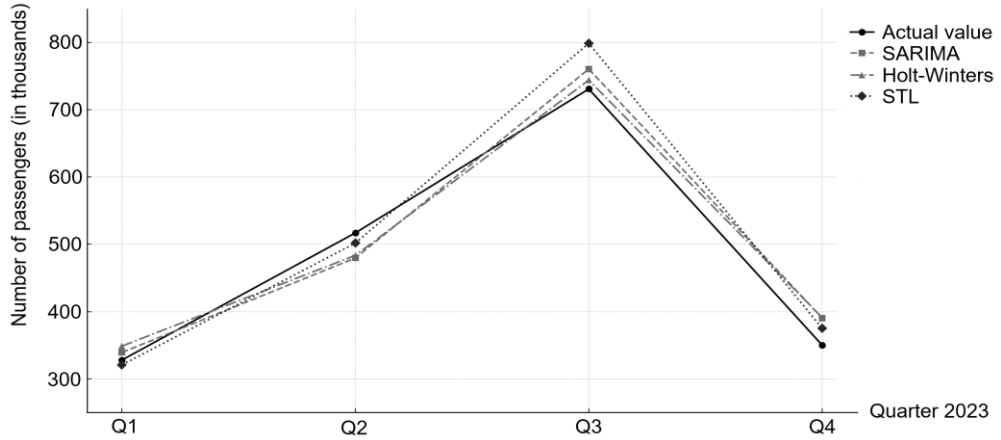
An example of the use of mathematical modeling to analyze and evaluate the functioning of transportation processes in crisis situations is the study of passenger traffic disturbances at Polish seaports. In the article (Sobczuk and Borucka, 2025) the authors assessed disruptions caused by COVID-19 pandemic 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:

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

$$CO_2T - 2.467 \times GREV - \ 1.807 \times TREND = 0 \tag{2}$$

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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