Journal of Advanced Transportation

Innovative Technologies for Sustainable Passenger Transport

Lead Guest Editor: Ondrej Stopka
Guest Editors: Stefano Ricci, Marin Marinov, Borna Abramović, and Vladislav Zitricky

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Editorial

Innovative Technologies for Sustainable Passenger Transport

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Functional transport systems represent an important place in terms of the population mobility and generate a prerequisite for the economic-related development among individual regions. Population mobility increase in recent decades also pushes a question regarding the sustainable development of various world economies. However, a growing need to travel brings negative environmental impacts and points to the necessity for environmental protection. Technological premise creates the prerequisites for organizing, operating, and managing traffic and transport with as little negative environmental impacts as possible and helps to create a system of sustainable mobility. An option to develop transport systems consists in the implementation of innovative technological solutions applied within passenger transport processes.

For a successful transport process optimization and its consequent execution, it is necessary to define individual activities needed to carry out the entire process. Activities can be divided into individual levels, whereby the better orientation in the process can be achieved. In order to efficiently optimize individual activities within transport processes, operations research methods and information technologies can be applied. The current problem is to solve the sustainability of technological developments in assuring the quality of life for future generations. Trend of innovate and smart technologies does not eliminate transport and its processes from the problem of sustainability. The question of these days is whether the introduction of innovative and smart technologies can guarantee the sustainability of transport processes also for the future.

In the presented special issue, lead guest editors received 17 manuscripts of research articles. In total, 7 articles (86 pages) out of 17 have been successfully reviewed by the reviewers and subsequently published.

The article entitled "Research of the Passenger's Preferences and Requirements for the Travel Companion Application" deals with a research of the passenger's preferences and requirements for the travel companion. The research study consists of four steps based on analyses of interaction points, interviews, and workshops. Each step of the proposed methodology brings interesting feedback on the design and functionality of the travel companion. The paper is based on particular results of the "H2020 project - 730842 Governance of the Interoperability Framework for Rail and Intermodal Mobility (GoF4R)".

The article "Challenges for Air Transport Providers in Czech Republic and Poland" brings the readers an insight into the elements of demand placed within air transport, particularly possibilities of increasing the demand for air transport in Central Europe, especially in the Czech Republic and Poland.

The article "Urban Transformation in the Context of Rail Transport Development: The Case of a Newly Built Railway Line in Gdańsk (Poland)" discusses the mutual relationships among operation of a newly built railway line and spatial changes taking place in its closest vicinity which determine the accessibility to it. The proposed research methods, within this research study, include the GIS tools, direct measurements of passenger exchange, and public opinion poll among the passengers taking the new line. The city of Gdańsk in Poland was considered the research area.

The article "Approach to the Weight Estimation in the Conceptual Design of Hybrid-Electric-Powered Unconventional Regional Aircraft" is focused on the development of an innovative approach to the weight estimation in the conceptual design of the Hybrid-Electric-Powered (HEP) Blended Wing Body (BWB) commercial aircraft. The research within this article explores the potentialities of an energy-based approach for the initial sizing of HEP unconventional aircraft in the early conceptual phase of the design. A detailed parametric analysis has been carried out to emphasize how payload, range, and degree of hybridization are strictly connected in terms of feasible mission requirements and related to the reasonable expectations of development of electric components suitable for aeronautical applications.

The article "Aspects of Improvement in Exploitation Process of Passenger Means of Transport" is oriented toward analyzing and evaluating the system of exploitation of passenger transport means and proposing solutions for its improvement. Based on the theory of exploitation systems, quantitative utilitarian models have been built, which have been verified by applications using data obtained from Municipal Communication Company (MPK) in Wroclaw. Originality and innovation in the recognition of this research problem consist in applying the analysis and evaluation of the Ishikawa diagram exploitation system, Pareto-Lorenzo analysis, and FMEA (Failure Mode and Effects Analysis) methods. On the other hand, a QFD (Quality Function Deployment) diagram was used to build a model of improvement of the exploitation system, with the use of which the target values of parameters for the operation of MPK passenger transport in Wroclaw were determined. The applied methods and research techniques are rarely used in the field of testing of vehicle operation systems.

The article "Theoretical Comparison of the Effects of Different Traffic Conditions on Urban Road Traffic Noise" investigates the effect of different traffic conditions on urban road traffic noise. The results of this research study showed that traffic congestion had considerably the maximum peak compared to other traffic conditions which would highlight the importance of the range of generated noise in different traffic conditions.

The article entitled "Integrating Bus Holding Control Strategies and Schedule Recovery: Simulation-Based Comparison and Recommendation" presents an examination of the effect of bus drivers behavior on bus holding control strategies and more specifically their effort in catching up with schedule in case of delay, i.e., schedule recovery. Based on the analysis and proposed solution, research study shows outcomes providing an insight into the bus stop layout design and implementation of holding methods in the context of cruising guidance.

The editorial team hopes that this particular special issue will be interesting for the great variety of readers and help them in terms of their scientific and research activities to make progress in implementing and developing the sustainable transport and mobility.

Conflicts of Interest

The guest editors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

Last but not least, the editorial team would like to thank all the reviewers for the time they spent to evaluate presented articles, and is even more grateful for their constructive comments, remarks, and suggestions for authors in order to revise and modify their articles. After all, all of it has helped to publish these research works.

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Research Article

Research of the Passenger's Preferences and Requirements for the Travel Companion Application

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Currently, passengers have access to a lot of information when planning their trip by public transport. They can use a lot of applications, which are not compatible with each other. Sometimes it can be even quite difficult to collect all relevant information. The creation of one application (Travel Companion), which contains all relevant data needed for optimal planning of a trip can make travelling by public transport more attractive. This paper identifies and describes conditions for a large market uptake of the Travel Companion approach by the end-users: the travellers. The paper deals with research of the passenger's preferences and requirements for the travel companion. Research consists of four steps based on analyses of interaction points, interviews, and workshops. Every step of methodology brings interesting feedback on the design and functionality of the travel companion. The paper is based on particular results of the H2020 project - 730842 Governance of the Interoperability Framework for Rail and Intermodal Mobility (GoF4R).

1. Introduction

The increase in individual car transport brings many problems, including congestion, air pollutions, energy consumption, and other negative effects to environment [1]. This negative effect can be eliminated by an increased use of public transport, which is environmentally friendlier than individual car transport [2] and is a way how to develop sustainable mobility. Airports, ports, railway, metro, and bus stations should increasingly be linked and transformed into multimodal connection platforms for passengers to increase the use of public transport [3]. Alonso et al. [4] compared passenger transport sustainability in European cities. They propose an analysis of sustainability of urban passenger transport systems based on available indicators in most cities and created composite indicators to measure the sustainability of urban passenger transport systems. Rail transport has a key role in the urban passenger transport system. However, in the many large agglomerations there are problems with the available capacity of railway lines. [5, 6]. The European Commission is encouraging a modal shift towards railway, what is considered as one of the key factors for the development of a more sustainable European transport system. The coveted increase in railway share of transport demand for the next decades and the attempt to open up the rail market (for freight, international, and recently also local services) strengthen the attention to capacity usage of the system [7]. However, railway transport must be integrated with all modes of public transport [8].

Public transport has to be more comfortable and attractive for passengers. Customers are influenced by many factors when choosing a mode of transport. Psychological factors have an important role among them. Understanding the psychosocial factors that influence public transportation usage behaviour can provide important implications for transport policies aimed at managing travellers' mobility behaviour [9]. Another important factor is an access to the relevant timely information. Monzon et al. [10] describe how Real Time Passenger Information systems help people change their travel behaviour towards more sustainable transport modes. It could significantly contribute to decarbonising the EU passenger transport system [11].

Currently, there are a lot of noncompatible applications designed to find the information for the passenger but it is necessary to combine the data from these numerous applications to find all needed relevant data about the journey. Stopka [12] was dealing with user requirements for mobile application to support door-to-door mobility in public transport. These applications are often created by transport operators for coordination of timetables, synchronising arrival and departure times between the different transportation modes, and the traveller information system [13].

Bak and Borkowski [14] researched the applicability of Information and Communications Technologies solutions in passenger transport from the perspective of transport users taking into consideration real case studies from different European backgrounds. Their main conclusion was that users in various regions with very different characteristics such as wealth, GDP levels, geography, and cultural back-grounds represent surprisingly similar attitudes towards Information and Communications Technologies.

This paper shows the particular results of project H2020 - 730842 Governance of the Interoperability Framework for Rail and Intermodal Mobility (GOF4R) about passenger preferences/requirements to the 'Travel Companion' (TC) application, which functions as a 'front end' user interface, giving users full control of their door-to-door travel experience [15]. TC stores and shares passenger's personal preferences in a wallet. It will give access to all travel services needed for the journey, shopping, and booking and allow storage of the rights to travel. At the same time, retailers and operators will be able to identify and authorise the TC to access their own systems and networks [16].

Paper is focused directly on the results of Work Package 2 User demand. General objective of WP2 is to map the current and future demand for the Interoperability Framework (IF) and the specific objectives are to analyse the market actors' interests in the IF and to analyse the travellers demand for the Travel companion. Travellers can use the Travel Companion (which considers personal preferences, including mobility constraints) to plan their trip, manage bookings, validate entitlements, navigate at interchanges, and, in case of disruptions, find alternative solutions for rerouting and reaccommodation. In the 'back end', the 'Interoperability Framework' (IF) provides technical interoperability of multimodal services by insulating consumer applications from the task of locating, harmonising and understanding an open-ended world of data, events, and service resources, which are consequently made available 'as a service' [17].

The GoF4R project is the follow-up to the results of IT2Rail project. Objective of the GoF4R project is to define sustainable governance for the interoperability framework that will create the right conditions to introduce seamless mobility services and foster the development of multimodal travel services. GoF4R will help to overcome obstacles currently impeding development of market innovation by fostering a large acceptance of the "semantic web for transportation." The project and the paper are not oriented on developing the Travel companion or any other applications and their usage on the market. There actually exist many TC provided by municipalities, regional, or national carriers in every kind of transport mode. But there does not exist a defined sustainable governance and interoperability framework for their vertical and horizontal cooperation.

2. Materials and Methods

There is extensive literature concerning the factors that can influence (positively or negatively) the adoption of new technologies by consumers as well as research methods to analyse behaviour of passengers. A brief synthesis of the seminal works in this field is described in Table 1.

Different models coexist with a diversified range of factors, but it is possible to identify recurrent elements, that are consolidated in the literature:

(i) Performance expectancy: the degree to which using the Travel Companion will provide benefits to consumers in different phases of the travel experience (i.e., perceived usefulness)

(ii) Effort expectancy: the degree of ease associated with consumers' use of the Travel Companion (i.e., ease of use, usability of technology)

(iii) Social influence: the extent to which users perceive, that important others (e.g., family and friends) believe they should use the Travel Companion and in turn promote it to their peers

(iv) Compatibility with current resources: the degree to which the Travel Companion can rely on available resources/technologies like smartphones or similar

(v) Habit: the extent to which people tend to repeat behaviour automatically because of learning

(vi) Hedonic motivation: fun or pleasure derived from using the Travel Companion

(vii) Value for money: value/monetary benefit or superiority compared with alternatives

(viii) Perceived risk: the perception of safety and security in providing private information

(ix) Reliability and trust: the reliability of the information that users obtain and the trustworthiness of the provider (keep promises, keep consumers' interests in mind)

Table 1: aTable 1: State-of-the-Art.

Method	Authors	Author's access description
Concepts of perceived usefulness	Davis [20]	First introduced the concepts of perceived usefulness and ease of use.
UTAUT (Unified Theory of Acceptance and Use of Technology)	Venkatesh et al. [21]	Defined the UTAUT according to which the main concepts influencing the use of a technology are: performance expectancy, effort expectancy, social influence, facilitating conditions and attitude towards using technology.
	Venkatesh et al. [22]	Refined UTAUT to UTAUT2 with the addition of some further factors: hedonic motivation, price value and habit.
	Wang et al, [23] Pura [24] Slade et al. [25]	Integrated the UTAUT model with other factors like perceived risk, trust, behavioural intentions, monetary value.
"World Café"	Fenton, (n. d.) The World Café Community Foundation, 2015	Described Word Café method.
Ethnographic research	Goetz and LeCompte [26]	Dealt with strategies for analysing records or transcripts of human behaviour. They described some techniques such as the constant comparative method, typological analysis, enumeration systems, and standardized observational protocols.
	Fetterman [27]	Described ethnography as "the art and science of describing a group or culture"
	Narain [28]	Used qualitative research design, an ethnographic approach and a diversity of data sources showing how social heterogeneity, land use change and other transformations in rural-urban links brought on by urbanization shape periurban transportation needs and practices.
	Jordi [29]	Used ethnographic research for analysis a socio-cultural point of view perceptions about the health of those who use bicycles as means of transportation.
	Cass and Faulconbridge [30]	Dealt with theoretical insights into understanding everyday travel (from the mobility turn and theories of social practice) in an analysis of everyday mobility using data from ethnographic research.
	Jones et al. [31]	Used an ethnographic study for making sense of new transport.
	Gossling and Stavrinidi [32]	Designed and embedded in a grounded theory approach, the study investigates the mobility patterns of one Generation Y network based on an ethnographic research.
	Brown, Iacono [33]	Described that ethnographic research produces an extra-ordinary depth of knowledge on the context of the research study and can therefore produce rich insight into the problem.

(x) Learning effects: the ability of the Travel Companion to learn from previous searches, preferences, etc. to improve suggestions, routes, etc. to users

Many research methods can be used to analyse the behaviour of a passenger. Interviews, ethnographic workshops, and international expert workshops were used in this project. Ethnographic workshops and international expert workshops were realised on the World Café principle. Respondents were common passengers/potential passengers at the Ethnographic workshops and transport experts at the International expert workshop.

A "World Café" is a common method for fostering interaction and dialogue within large or small groups [18, 19]. It is particularly effective in identifying the collective wisdom of large groups of diverse people. The format is very flexible

A

	Consumer interaction points	IT2RAIL concepts
On-going communication	User identity	User identity / E-passport / Wallet
	Preferences	Preferences
	Planning	Location resolver / meta-network Construction / multimodal shopping / booking and ticketing
	Buying	Wallet
	Receiving entitlement	Booking and ticketing / Wallet / E-passport
	Information	Trip-tracking / interchange navigation / business analytics
	Disruption	Disruptive ticketing and validation
	After trip	Business analytics

B

Figure 1: Overview of TC consumer interaction points & corresponding IT2Rail concepts.

and adapts to many different purposes: information sharing, relationship building, deep reflection, exploration, and action planning. The host begins by putting participants at ease. The process then consists of rounds of approximately 20 minutes of conversation for each group on a specific question or item that needs to be explored and discussed. At the end of each round, everyone moves to another table. The moderator summarises after every change what was said in the previous group. One group continues on the findings of the previous group. Afterwards, insights gathered by each table are shared with the larger group and presented visually, for example, by means of graphics.

The methodology of research within the GoF4R project consisted of 4 steps:

(i) As a first step, the Travel Companion has been 'deconstructed' into its consumer-oriented capabilities and interaction points.

(ii) For each interaction point, a series of assumptions have been formulated with regard to factors (incentives, needs, constraints, barriers) that could (positively or negatively) influence the consumer uptake of the TC approach. These assumptions were validated by means of interviews with relevant stakeholders.

(iii) Workshops were organised in Belgium, Italy, Slovakia, and the Czech Republic, in order to better understand the conditions for market uptake of the Travel Companion approach and to assess potential ethnographic differences between countries and cultures.

(iv) Finally, the findings obtained during the interviews as well as the national workshops were presented and further discussed at a European-wide workshop with Shift2Rail IP4 members and other experts.

3. TC Consumer Interaction Points

Based on the results of IT2Rail project TC should be conceived as the interface between the traveller (user) and the travel and transportation network system which

(i) supports the user in all phases of the travel: preparation, execution and after-trip operations;

(ii) stores travel-related documents.

IT2Rail focuses on a number of concrete use cases, specific instances of an individual traveller's journey, that follow the traveller throughout the different stages of planning, booking, and executing a multimodal journey, in order to better understand actual user needs along the way.

Without going into details about code information and IT technicalities, it is for our purposes interesting to consider the Travel Companion (TC) from an end-user point of view in order to understand how it could work in practice.

The IT2Rail concepts have been taken as a starting point to define 'consumer interaction points', i.e., all those situations in which the Travel Companion may assist the user in different phases of the travel experience (Figure 1). The main consumer interaction points are described below.

User identity: in order to be able to use the Travel Companion, users will need to register and create an account. They will also be asked to provide some personal information (for example, name, address, age, gender, e-mail address, phone number, payment details). The aim is that the Travel Companion will thus be able to provide the user with customised assistance and information.

Preferences: a consumer will need to complement the user identity with their individual preferences. Some of these preferences may be transport related, e.g., PRM status, seating preferences, and modal choices (possibly linked to weather or other circumstances, e.g., working day-weekend, business-leisure) and some may not be transport related, e.g., preferred social media, dietary needs, etc.

Planning: travellers can use the TC to plan their journey from A to B comparing different travel options and combining different variations of transport modes. The TC can provide personalised routing results according to the user's specific travel preferences or needs, including, for example, the fastest or cheapest route. A user might reiterate a planning request, altering the input or the preferences.

Table 2: Overview of the workshops.

Date	City & country	Number of participants	Responsible partner
30/10/2017	Ghent (Belgium)	12	European Passengers' Federation
07/11/2017	Žilina (Slovakia)	18	University of Žilina
07/11/2017	Milano (Italy)	28	Politecnico di Milano
20/11/2017	Brno (Czech Republic)	12	University of Žilina
22/11/2017	Bratislava (Slovakia)	18	University of Žilina

Buying: after planning a journey, a user will have the possibility of buying a ticket/entitlement. This is a separate step because not all planning will lead to buying.

Receiving entitlement: after paying for the journey, the ticket or entitlement will be stored in the Travel Companion (primary carrier). As a back-up (in case the smartphone cannot be used), the E-passport is planned to store data on the user's journey within its NFC chip.

Information: a traveller will need different types of information during the trip: both transport related and possibly also nontransport related (e.g., information on the weather, shopping, tourist information, food and drinks, etc.). The TC will be able to offer context-dependent information, based on the current location of the traveller (using the GPS and possibly the accelerometer in the user's smart device), which could, for example, be useful in the case of navigation at interchanges.

Disruption: when a disruption occurs, a traveller will interact with the Travel Companion most likely a multitude of times to plan alternative solutions and to receive information.

After trip: after the trip, the user will be able to interact with the Travel Companion to give feedback on the trip and/or receive additional information in case something went wrong.

On-going communication: since travelling carries a certain degree of uncertainty, a user will seek on-going communication throughout the journey.

For each interaction point, we aim to identify possible needs/expectations as well as barriers/constraints from the point of view of the end-user: the traveller.

The methodology of our research consists of 3 steps; in the first round interviews were done with specialist from the praxis (carriers, transport authorities, governance) for defining the needs/expectations and the barriers of the TC. Results from the first round were used as a base for the second step. In the second round we got information from random passengers about their travel preferences, which the TC should take in account. These workshops were the main part of the research. In the last round the mismatched opinions of the passengers were consulted with experts in the field of transport.

3.1. Interviews. The purpose of the interviews conducted within the research was to collect information on the following:

(i) What are the needs experienced by the customers in connection with the TC?

(ii) What factors are relevant 'in general' to explain customers' the TC adoption?

  (a) What factors can obstacle the TC use?
  (b) What factors can facilitate the TC use?

(iii) What factors are relevant for each interaction point (cf. above) and how could they influence the customer acceptance and use of the TC?

When selecting potential interviewees the following profiles were used:

(i) Familiar with consumer-oriented ICT applications

(ii) Preferably with expertise in consumer sciences (psychology, behavioural sciences, marketing, user-centred design, user experience researcher)

(iii) Preferably with expertise in Human-Machine Interaction

(iv) Mobility professional but she/he can also be active in another sector as long as she/he has a strong consumer focus

The study also aimed at collecting a relative coverage of the whole mobility sector (local, urban transport, rail, car, aviation, etc.).

In total, 16 in-depth interviews were carried out for research with experts from 5 different countries.

To ensure basic information, uniformity and as much objectivity as possible, interview guidelines were developed including 28 prepared questions to structure the interviews.

The interviews were divided into 9 main sections related to the above-mentioned 'interaction points' between the Travel Companion and its user. The answers have been recorded and translated into English and have been sorted so that all of the answers to each question are presented together to allow for comparison and analysis of the results. A summary of the results from each question is presented in the following section of this report along with the conclusions.

3.2. Ethnographic Workshops. In order to collect further information on factors that could influence the uptake and use of the Travel Companion (building upon the findings of the interviews), and also to detect possible cultural/ethnographic differences (East/South/West-Europe), five workshops were organised (Table 2).

People were chosen on the basis of random choice with reflecting the structure of the potential passengers: students,

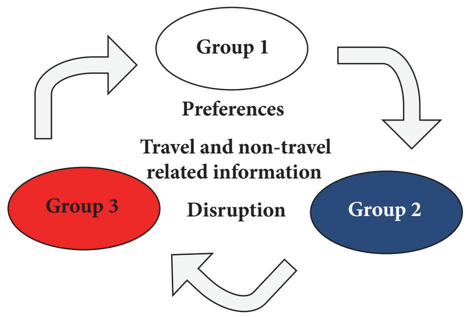

FIGURE 2: The World Café method was used to discuss three topics (In the Milan workshop, four teams each discussed two topics).

seniors, employees, nonemployees, men and women, user and nonuser of public transport.

To ensure basic information, uniformity, and comparability of results, workshop guidelines were developed including tips on how to select participants, how to organise the workshop, themes to be addressed, workshop methods to be used, and reporting instructions.

The target number of participants was 15/20 per workshop. The method used for selecting participants is the so-called 'purposive' or 'convenience' sampling. The focus group approach being a qualitative methodology does not aim at providing results that describe how an entire population would respond to the same questions, but aim to achieve a better understanding on how users relate with a certain topic, through a discussion and a comparison between participants' personal attitudes towards the theme. In selecting participants to be invited to the workshop, attention was paid to the following criteria:

(i) Balance between men and women
(ii) Balance between younger and elderly people
(iii) Inclusion of at least one person with reduced mobility
(iv) Balance between experienced and nonexperienced travellers
(v) Balance between regular and nonfrequent travellers
(vi) Balance between digital natives and digitally impaired travellers
(vii) Inclusion of people that travel for different purposes (business, leisure, other)
(viii) Inclusion of people that travel both within their own country and outside their own country

The workshops all lasted 2-3 hours and were held in the local language. The workshops all followed a similar structure:

(i) Introduction
(ii) First round: discussion on three topics (preferences, travel related & nontravel related information, disruption & feedback) using the World Café method (Figure 2)
(iii) Second round: discussion on barriers and incentives to use the TC

Each workshop started with a brief introduction of the GOF4R project, the workshop objectives and a description of the Travel Companion and its functionalities, followed by a short round of acquaintance (20 mins in total). Then, the participants were divided into smaller groups.

During the first round of discussion (ca. 50 min.), the World Café method was used to tackle three topics.

The three topics discussed during the first round in each workshop were as follows:

(1) Preferences

(i) Do you think that the ability to indicate their preferences will be considered by users as an incentive to use the Travel Companion and/or could it be a barrier? Please explain.
(ii) Do you think more people would use the TC if it is not necessary to set preferences first?
(iii) Which preferences do you think are most important?
(iv) Do you think the Travel Companion should 'remember' preferences from previous choices the user has made when planning / booking a trip?

(2) Travel related info vs. nontravel related info:

(i) Travellers especially need information on cost, travel/transfer time, travel modes and transfer points. Are any important items missing from this list? If so, what is missing?
(ii) Is it useful that the Travel Companion provides nontransport related information too? If so, which are most relevant?
(iii) The Travel Companion will be able to offer context-dependent information, based on the current location of the traveller (using the GPS and possibly the accelerometer in the user's smart device). Could this be a barrier for using the TC or do you think it will more likely be an incentive?
(iv) Should users be able to communicate with other travellers on the same route (e.g., to find out where in the vehicle there are any free seats left)? Why (not)?

(3) Disruption / feedback:

(i) Which kind of assistance should be offered by the Travel Companion in case of a disruption? (planning an alternative route, offering the possibility to 'buy' a new ticket, offer also nontransport related information, e.g., on accommodation, food/drinks, and so forth).
(ii) Should the TC only communicate about how the journey is going in case of disruptions or also reassure the user during the journey if everything is going according to plan?

Barriers for the use of the Travel Companion

Personal information / preferences
- Time-consuming
- Privacy and security
- Ease of change
- Transparency (options you get)

Information provided by TC
- Reliability (are all option integrated)
- Accuracy (real-time info, up-to-date)
- Transparency (option you get)
- Complexity (too much info)

Communication / feedback
- Bad support
- Reliability (help function)
- Privacy

Payment / transaction
- Trust
- (Cyber)security
- Complexity
- Habits

Tool / app
- Complexity
- Habits
- Added value compared with other apps
- Extra cost / savings
- Use by family and friends

Providers
- Trust
- Reliability

Figure 3: Barriers for the use of the TC.

(iii) What kind of information should the Travel Companion offer the user after the trip has finished? (e.g., lost property, how to file a complaint, information on passenger rights).

(iv) Which options for on-going communication should be offered by the TC? (e.g., chat, social media, hotline, personal assistance, SMS, and notifications on the TC).

In the second round of the discussion (ca. 40 mins), workshop participants were asked to discuss potential barriers for the use of the Travel Companion. They were presented with a map showing the most important barriers detected in the interviews (cf. above) and asked how to get rid of these barriers (Figure 3).

In a final part (ca. 15 mins), each group was asked to think about incentives to use the TC. Which functionalities/characteristics would they highlight? How would they try to reach certain target groups? Which communication channels would they use? What type of campaign would they propose? What are the main advantages of the TC compared with existing travel apps?

3.3. International Expert Workshop. An international expert workshop was held in Brussels (UIC premises) on December 5th 2017. The workshop had the following objectives:

(i) Exchange knowledge between different IP4, S2R and other experts

(ii) Validate findings of the end-user research done so far in the research

(iii) Detect the (potential) implications of the user requirements on the IF and its governance

24 people attended the workshop, including 14 external experts (from outside the GOF4R consortium) from different countries and different fields of expertise.

To start with, the participants were introduced to the Shift2Rail programme and the GOF4R project. The Travel Companion's objectives and functionalities were presented as well as the main findings obtained so far from the interviews and national workshops. A 'tour de table' followed in order for all meeting participants to present themselves. In particular, the external experts explained their experience and connection to this and other EU-projects and their expectations.

4. Results and Discussion

The fields of our research and their particular results are described in Figure 4.

More detailed research results are described in the next chapters.

4.1. Interview Results. The interviews have provided valuable feedback on the design and recommended functionality of the Travel Companion. From these the following design considerations should be implemented:

(i) It should be possible to use basic functions such as journey planning without registration.

(ii) Registration and setting preferences should be kept simple and information should only be requested when it is required. It should in that case also be clear to the user why it is required and how it will be used, they should be able to understand the benefits from this.

(iii) The user should have the option for the TC to remember any preferences.

(iv) The TC should be transparent on options you get when you plan a trip (linked to preferences).

(v) Complexity of the tool was identified as the greatest barrier, so simplicity should be prioritised.

(vi) Another primary barrier is trust: the TC must provide a trusted platform for e-commerce and build up trust in providing the most appropriate ticket prices and real-time info.

(vii) The opinions were mixed regarding whether payments should be before or after trip. The advantages

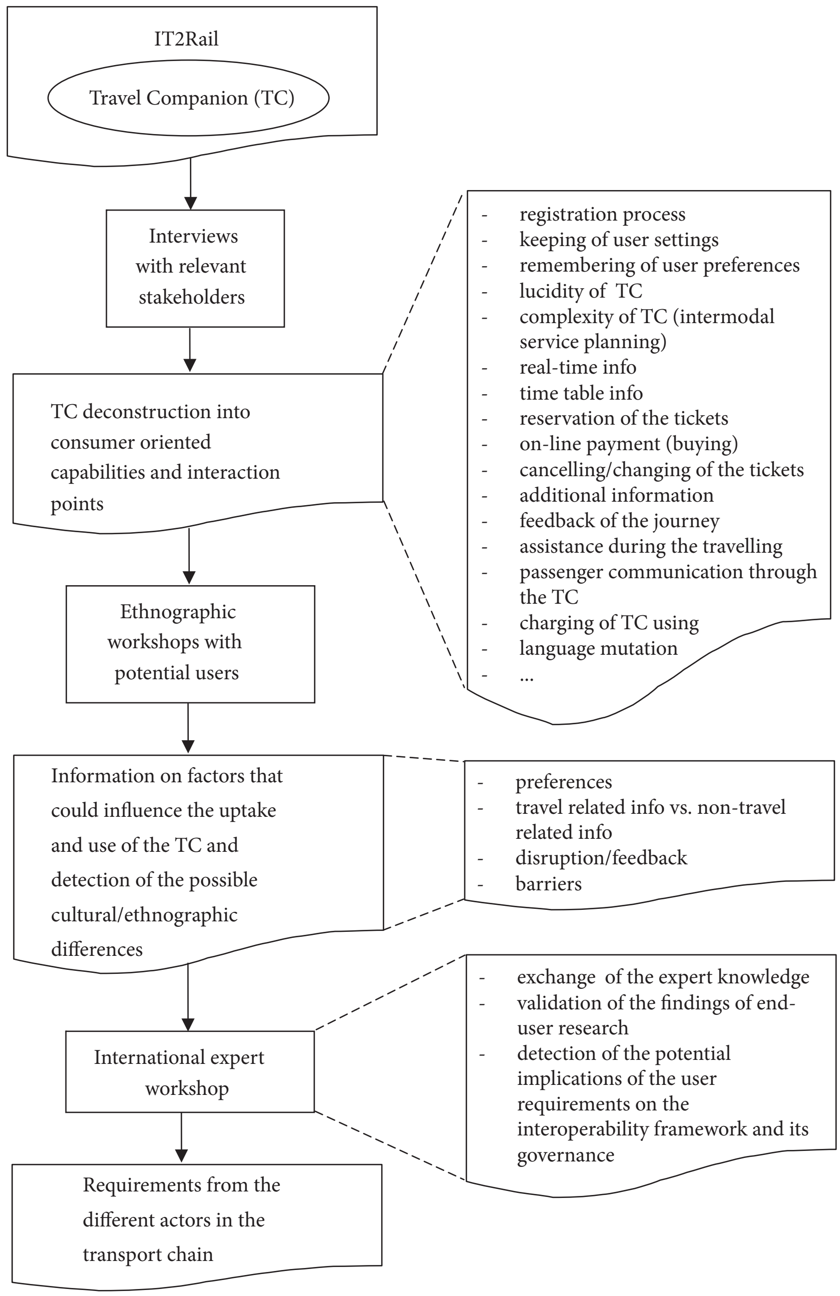

Figure 4: Partial topics of research.

of post payment were that it is easier to provide compensation/discount in case of disruption. But customers are used to prepayment for purchasing public transport journeys. Post payment could be an option for business users or frequent travellers.

(viii) The TC should allow the users to buy tickets for others.

(ix) Most respondents felt that there was no benefit to storing tickets on an NFC chip. Instead, QR codes which could be printed or displayed on a mobile device are considered preferable.

(x) Flexibility was highlighted as a key user requirement and the ability to cancel or change tickets, although charges may apply for increased flexibility. There was also a concern that although a single ticket may be simpler for the user, it may result in less flexibility for the user to change sections of their journey.

(xi) Additional information may be useful, as long as it does not overcomplicate the tool, but also some information is available in alternative tools.

(xii) The ability to provide feedback on the tool and journey was considered as a useful functionality.

(xiii) The tool should provide a method and the data for claiming compensation, or automatically provide feedback.

(xiv) Assistance could be provided through the tool and would be particularly useful for PRM, children, and the elderly. However, it may present additional cost to the transport operators.

(xv) There were mixed reactions about passenger to passenger communication through the Travel Companion; it could be useful for arranging to share part of the journey, e.g., share a taxi, but could also degenerate. Also, many other social media tools are already available.

(xvi) The Travel Companion should be free of charge, unless it offers additional services.

(xvii) The Travel Companion should be available in language of the user.

4.2. Workshop Results. The main barriers to use the TC, identified during the national workshops, were:

(i) *Accuracy, related to information:* the tool should be able to manage extraordinary situations in real-time, signalling (as some existing apps already do) delays, strikes, changes in the status quo. Information (in particular, related to disruption) should be updated as often as possible and the replanning should be guaranteed and timely.

(ii) *Reliability related to information provided by the TC* has been detected as a key feature. The TC should be able to consider all possible options (first and last mile, special deals, and prices) and show them to users, so that they can check and to choose the best alternative.

(iii) *Profile/preferences: time-consuming:* users should be able to decide which information they want to register and it should be possible to enter only very little information. It should be possible to use the TC without creating a profile or set preferences first.

(iv) *The complexity of the tool/app:* participants agreed that it is a key issue to provide a smart and intuitive interface, avoiding complex and too technical issues.

(v) *Bad support during and after trip* is also indicated as a barrier. Users want to communicate with the tool when necessary and get personal assistance. Giving feedback should be as easy as possible. A simple yes/no question, choosing a smiley face or a sad face, thumbs up or thumbs down, and so forth are preferable over long questionnaires. Gamification and rewards could help to incentivise travellers to give feedback on the services. It would be useful if user feedback could also be given during the journey.

(vi) *Cyber security:* the TC should be as reliable/safe as competing applications in terms of on-line payment. The system must offer the payment method(s) that people prefer (which can differ from country to country). It may be a problem only if the user is generally suspicious of using any form of online payment.

(vii) *Existing habits:* most people already use an alternative app. TC has several competitors from which it has to differentiate clearly showing what its added value is. Habits become a problem when a user has a loyalty with a specific company that guarantees him some benefits. The TC platform could also release a fidelity card to avoid the issue.

(viii) *Privacy:* privacy concerns are related specially to profile (personal data) and buying (card details); however, this is not considered as one of the most important barriers.

The main incentives that were found in the workshops that can facilitate the uptake of the TC:

(1) Usefulness of the TC: today, organising complex, multimodal, European wide trips requires a lot of effort and is time-consuming. Travellers must adjust to a variety of interfaces, devices, tools, etc. The IF and the TC could make the planning & buying process a lot easier.

(2) Better protection of the passenger rights**:** in case of a disruption, the TC should offer full assistance, informing the user on alternatives, if the original plan is no longer feasible, and also on passenger rights and reimbursement procedures. Currently, passenger rights apply independently to each individual transport mode and only under a single contract of carriage.

(3) Accurate and reliable information**:** consumers need to feel confident that they receive an overview of the best travel solutions, taking into account preferences and needs. Reliability (of data, information) and transparency (e.g., how will the user's personal data be stored and processed) are two important aspects that will determine whether a traveller will use the TC. Crowdsourcing can be a good tool to complement information from 'official' sources.

4.3. International Expert Workshop Results. An international workshop with IP4 and other experts was held in Brussels on December 5th 2017, in order to validate the findings of end-user research done so far in project as well as to detect (potential) implications of these user requirements for the IF and its governance. Some interesting issues addressed during this expert workshop are listed below.

(i) Transport Service Providers should be stimulated to share data. For example, PTAs could include this as a contractual obligation in Public Service Contracts with PTOs.

(ii) It is important to integrate the data of small service providers and cycle infrastructure as well, in order to get a complete picture of what overall, the best travel options are.

(iii) For third-party players that aggregate (or sometimes scrape) data from different sources, it is important to have good quality datasets.

(iv) Various technical methods can be used to improve data provision, including the use of mobile phone sourced data (which implies a contractual relationship with providers).

(v) Different (or absent) approaches to open data exist in EU countries.

(vi) Regulation can make it easier to exchange data. The EC could, for example, provide guidelines on standardisation.

(vii) New business models can be developed to incentivise TSPs to share data and provide good data sets. The ‘roaming’ principle from the telecom sector was mentioned as a good example.

(viii) One of the biggest barriers for a small scale developer is the economics balance between marketing costs and ticket revenues.

(ix) A key issue is the speed and accuracy of the process to investigate the ‘raw’ data and turn it into useful information for the customers.

(x) Segmenting the data set (e.g., based on the type of trip or the type of traveller) can facilitate that the data fit the user’s personal needs.

(xi) Individual datasets should not be published. The GDPR is seen as a good initiative. It would save developers and TSPs time and effort if the EC could prepare clear guidelines on how to implement this Regulation in practice.

(xii) If existing UX research could be shared between all IF-stakeholders, this could be an incentive to cooperate (especially for start-ups who do not have large research budgets).

(xiii) The experts suggested to make the TC a modular tool so that users can start with a ‘simple’ version and if needed afterwards upgrade/expand.

(xiv) If possible, developers should adopt the principles of universal design to make sure also PRM can use the TC.

(xv) When a disruption occurs, TSPs should be forced to cooperate.

(xvi) A harmonisation of passenger rights across all modes is desirable.

(xvii) As an extra (paid) service, the TC could offer users an insurance that guarantees rescheduling in case of disruption. Paid in advance, this could be economically feasible.

(xviii) Crowdsourcing could be a good way to improve reliability of data, on the condition that there is a critical mass and that cross-reference with official channels is made.

4.4. Generally Results and Discussions. Our research confirmed some part of the concept of Interaction points established in IT2Rail but some of them were not confirmed. The differences are listed below.

User identity:

(i) some customers do not agree with registration and using personal info in TC (e.g., when users search only information about the trip)

Preferences:

(i) the users require the individual preferences only at planning the trip; it was not confirmed

Planning:

(i) the users prefer simplicity of the TC before complexity mainly for planning of the short distance trips

Buying:

(i) the customers were afraid of e-commerce security of TC

(ii) the users require the possibility to buy tickets not only for registered users

Receiving entitlement:

(i) the potential users prefer QR code before NFC chip

Information:

(i) the users do not require additional information (weather, shopping, etc.); they require detailed information about travelling

Disruption:

(i) the users agreed with what the IT2Rail experts suggest

After trip:

(i) the potential passengers require easy feedback (simple click to the icons at TC)

The results of our research show that potential users of the TC require a simple system of the TC, access to the main function without registration, flexibility (the possibilities of changing the kind of transport, final destination, etc.) mainly in unexpected situations in traffic (riots, accidents, natural disasters, etc.), protection of personal data, and secure platform for e-purchasing.

In case of real use of the TC it should be required to mandatorily share the information between all carriers (state, private) which offer public transport services and nonobligatory for other carriers. Design of TC should be universal with a modular structure. TC should offer valid and real time information, which is necessary for ordinary passengers as well as for businessmen.

5. Conclusions

In order to design and develop a sustainable and successful governance for the Interoperability Framework (IF) for semantic technologies that are being developed under the IP4 Shift2Rail programme (which is the overall objective of the GoF4R project), the requirements from the different actors in the transport chain need to be mapped and analysed. This paper presents the outcomes of particular results within GoF4R, which focuses on the "Analysis of the consumer demands and interest in using the TC capabilities".

As a first step, the Travel Companion has been 'deconstructed' into its consumer-oriented capabilities and interaction points, i.e. all those situations in which the Travel Companion may assist the user in different phases of the travel experience. The main consumer interaction points identified are: user identity, preferences, planning, buying, receiving entitlement, information, disruption, after trip, and on-going communication.

For each interaction point, a series of assumptions have been formulated with regard to factors (incentives, needs, constraints, barriers) that could (positively or negatively) influence the consumer uptake of the TC approach. In order to validate these assumptions, interviews were conducted with experts from different countries. In order to collect further information and to better understand the factors that could influence the uptake and use of the Travel Companion (building upon the findings of the interviews), and also to detect possible cultural/ethnographic differences, workshops were organised in Belgium, Italy, Slovakia, and the Czech Republic. And then finally a workshop with experts was held in Brussels, Belgium.

The interviews and workshops have provided valuable feedback on the design and recommended the functionalities, which the Travel Companion should have.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Challenges for Air Transport Providers in Czech Republic and Poland

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The aim of this paper is to find a trend in air transport behaviour in the Czech Republic and Poland, based on data collected between the years of 2004 and 2016. The choice of data period for the analysis was made because of the date when both mentioned countries joined the European Union and availability of data. The data used in this article is provided from the Eurostat web page where many revealing statistics are collected. The correlations of indicators were chosen as a method of the analysis. It was observed that the number of passengers increased up to 30% and 460%, respectively, in the Czech Republic and in Poland. The authors will explain possible reasons and aspects of such behaviour in order to make some predictions for future trends in air transport. The additional aim is to understand transport processes and economic growth in neighbouring countries during the period of focus. The knowledge of conditional changes in the number of passengers utilizing air transport grants the ability to make forecasts about the needed infrastructure, number of aircrafts, pilots, and staff needed at the airports.

1. Introduction

The increase in demand for air transport has led to specialization in a wide range of tasks. As a result of changes in the development of air transport due to the use of different tasks, it can be divided into transport aviation and general aviation [1]. Transport aviation is the transport of goods and mail in an organized manner by aircraft, i.e., airplanes, helicopters, and airships. This type of air transport is characterized by the highest transport speeds, adapted to the type of aircraft. The dominant mode of air transport is passenger transport. These may be scheduled flights, called scheduled flights, or nonscheduled flights, of which an example would be charter flights. In terms of coverage, we can distinguish between short, medium, and long-haul passenger aviation.

The attractiveness of air passenger transport is determined by the high standard of service, its speed, regularity, and safety. The statistical data confirms the safety of air services in comparison with other modes of transport.

All authors have strong mathematical and statistical background, and they would like to point out some dependencies, but they do not intend to interpret it very deeply from the economical point of view.

2. Methodology

There are various statistical methods and algorithms that can be used, so it is important to have a classification of the existing methods. The choice of method depends on the problem analyzed or the type of data available. The data mining process is guided by the applications. For this reason, the used methods can be classified according to the aim of the analysis. As a result, three main classes can be distinguished:

(i) Descriptive methods: they aim to describe groups of data more briefly; they are also called symmetrical, unsupervised, or indirect methods. Observations may be classified into groups not known beforehand (cluster analysis, Kohonen maps); variables may be connected among themselves according to links previously unknown (association methods, log-linear models, and graphical models). In this way, all the variables available are treated at the same level and there are no hypotheses of causality.

(ii) Predictive methods: they aim to describe one or more of the variables in relation to other; they are also called asymmetrical, supervised, or direct methods. This is performed by searching for rules of classification or prediction based on the data. These rules enable us to predict or classify the future result of one or more responses or target variables in relation to what happens to the explanatory or input variables. The main methods of this type are those developed in the field of machine learning such as the neural networks (multilayer perceptrons) and decision trees, but also classic statistical models such as linear and logistic regression models.

(iii) Local methods: they aim to identify particular characteristics related to subset interests of the database; descriptive methods and predictive methods are global rather than local. Examples of local methods are association rules for analyzing transactional data and the identification of anomalous observations.

The method based on the relationship between two or more variables was chosen to be the main method of the analysis. This method is usually called correlation; however in this analysis it is nonsensical correlation, an example being the correlation between a decreasing number of passengers in country A and country B. Such a correlation can be high simply because both variables are related to the state of economy [2].

To characterize this behaviour, parametric and nonparametric measures may be used to assess the relationship between the two characteristics. In this paper, a parametric measure called the Pearson coefficient has been applied, which determines the collinearity of the two features. It is described by the following formula [3, 4]:

$$r = \frac{c_{XY}}{S_x S_y} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}}, \quad i = 1, 2, \ldots, n \tag{1}$$

where $c_{XY} = (1/(n-1)) \sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})$ is an estimator of correlation cov(X,Y); S_x, S_y are estimators of standard deviation. If ρ—a population correlation—is zero, then the probability for a given sample correlation—its statistical significance—depends on the sample size [5]. Therefore, we combine the sample size and r into a single number, our test statistic t:

$$T = R\sqrt{\frac{n-2}{1-R^2}} \tag{2}$$

Now, T itself is not interesting. However, it is needed to find significant levels for some dependencies. T follows a t distribution with n-2 degrees of freedom [6]. The strength of the relationship varies in degree based on the value of the correlation coefficient [7].

2.1. Data Sample. The data used in this analysis is taken from the Eurostat web page [8]. The Eurostat web page is provided free of charge *via* Internet and its statistical databases are accessible *via* the Internet. The statistics are hierarchically ordered in a navigation tree. Tables are distinguished from multidimensional datasets from which the statistics are extracted *via* an interactive tool. The data from 31 European countries have been analyzed and they concern the years 2004–2016. The analyzed period was selected according to the day of joining the European Union by the Czech Republic and by Poland (2004) and availability of data (2016). These countries were selected due to nationalities of the authors and close economic relations between them [9]. Additionally, countries with a similar average of passengers in the investigated dates were chosen. The number of carried passengers is presented in Table 1 and in Figure 1.

One of the goals of this analysis is to find some indicators that can have an influence on the number of passengers in the future. The most used include

(i) the total number of distinct (unique) passengers that, in a given time interval, have travelled by plane,

(ii) mean passengers—the total number of passengers divided by the number of analyzed periods.

3. Results and Discussion

The group includes five member states of the European Union. Three of them—Austria, Belgium, and Finland—have very strong mutual correlations (Table 2). Poland is strongly correlated with Belgium and Finland. However, as for the Czech Republic, no correlation in regard to the rest of the group has been found. The discussed relationships are also visible in the graphs (Figure 4). This fact should be taken under analysis by economical experts.

3.1. Rate of Changes. In order to analyze the dynamics of air passenger transport, the rate of change was determined (Table 3). The rate of change is the speed at which a variable changes over a specific period of time. The rate of change is often used in regard to momentum, and it can be generally expressed as a ratio of a change in one variable relative to a change in another.

Year 2004 was chosen as the base. It is shown in the table that the number of passengers increased every year. The knowledge of the value of an increasing factor is very important especially in the forecast analysis [10, 11]. Based on

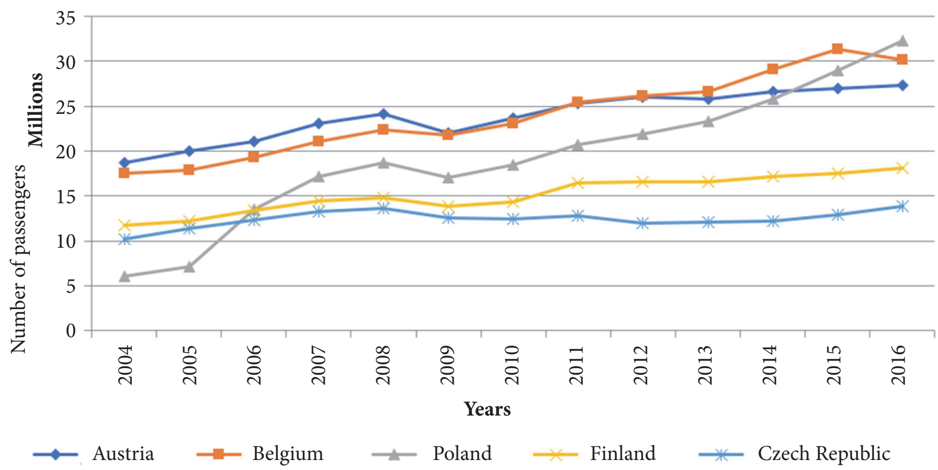

FIGURE 1: Number of passengers over the course of the analyzed years.

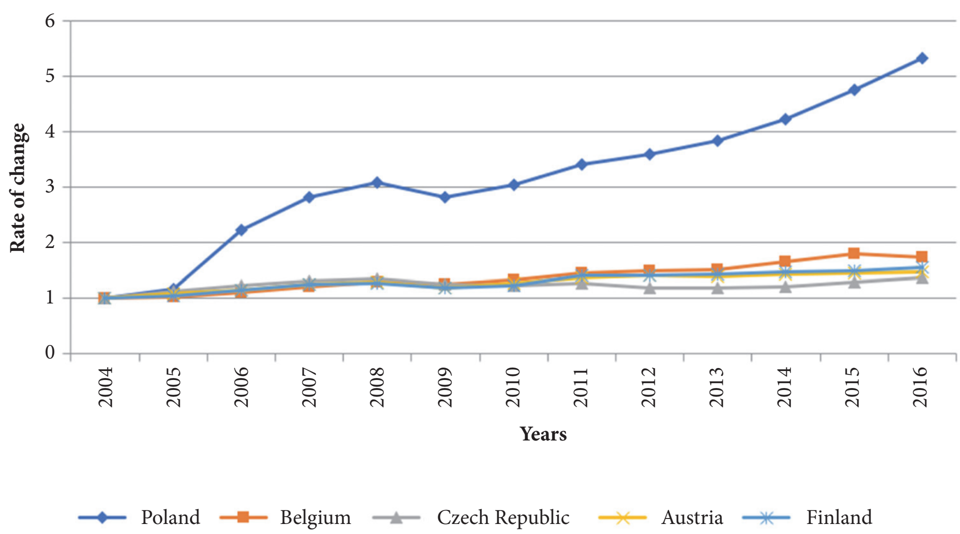

FIGURE 2: Rate of change over the course of the analyzed years.

the presented trends, it can be predicted that in a few years a higher number of pilots and staff at the airport will be needed.

The rate of change is also presented in Figure 2. Based on the rate of changes shown, it can be concluded that the biggest growth is seen in Poland, while the smallest is in the Czech Republic. The authors of the paper do not intend to interpret results from the economical point of view but they are going to point out some possible causes of such a situation. One of them can be the usage of other means of transport in the analyzed countries [12]. The number of passengers who use the international railway is presented in Figure 3.

The number of passengers has been compared with the number of citizens and with the area of the Czech Republic and Poland. Results are presented in Table 4. It has been observed that, in 2004, the ratio of the passengers to citizens was 5 times smaller in Poland than in the Czech Republic. The number of tourists was also significantly smaller. One of the reasons for such a situation can be the level of net salary (the salary which is left after deducting tax and National Insurance contributions). The ratio of net salary in the Czech Republic and in Poland is presented in Figure 5.

The net salary can also have an influence on the number of passengers. The comparison between Poland and the Czech Republic is presented in Figure 4. The ratio between salaries in the Czech Republic and Poland is presented in Figure 5. It can be concluded that the discrepancy between both countries in net salaries is decreasing.

4. Conclusions

The knowledge about the number of passengers and the trends of changes will allow for predictions about the needs of air transport in the future. One of them is the number of pilots. One of the possibilities is to graduate from the academy in Dęblin. It takes around 5 years and a number of flight hours. Another possibility is to acquire a flight license on

Table 1: Number of air passengers in the period 2004–2016 in five selected European countries (source: own elaboration on the basis of the Eurostat data).

Country	Year													
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Mean
Austria	18 700 556	20 016 059	21 081 247	23 098 068	24 089 381	22 009 610	23 704 171	25 284 604	26 082 777	25 827 030	26 566 052	26 981 962	27 382 263	23 909 521
Belgium	17 570 003	17 916 933	19 292 959	21 018 179	22 340 256	21 716 376	23 040 467	25 392 544	26 176 243	26 599 120	29 100 994	31 353 123	30 207 135	23 978 794
Czech Republic	10 153 848	11 366 681	12 329 375	13 266 743	13 643 795	12 571 098	12 427 085	12 824 895	11 927 281	12 027 537	12 210 556	12 957 296	13 830 127	12 425 870
Finland	11 700 311	12 224 922	13 330 288	14 428 108	14 848 534	13 828 492	14 273 836	16 448 435	16 514 915	16 606 783	17 211 934	17 475 353	18 097 108	15 153 001
Poland	6 091 643	7 080 176	13 546 393	17 154 688	18 729 811	17 092 396	18 433 984	20 676 295	21 871 076	23 298 404	25 743 021	28 974 650	32 341 649	19 310 322

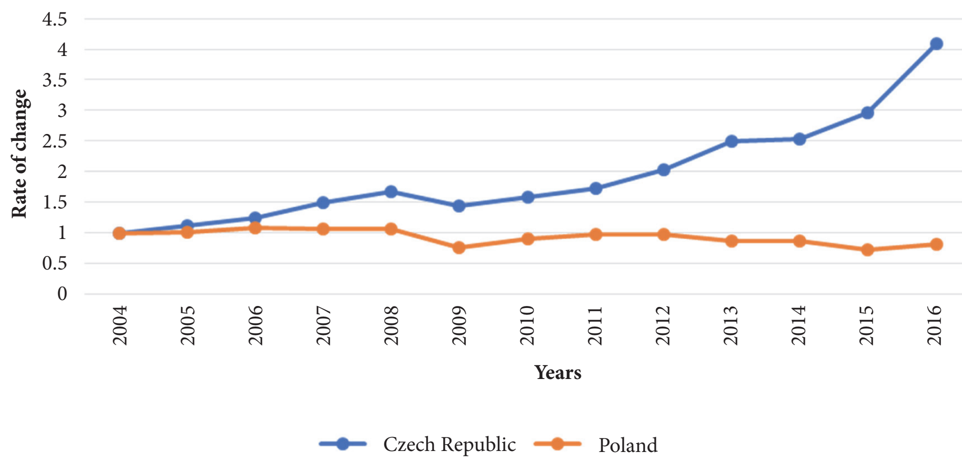

FIGURE 3: Rate of change of number of the railway passengers in the Czech Republic and Poland.

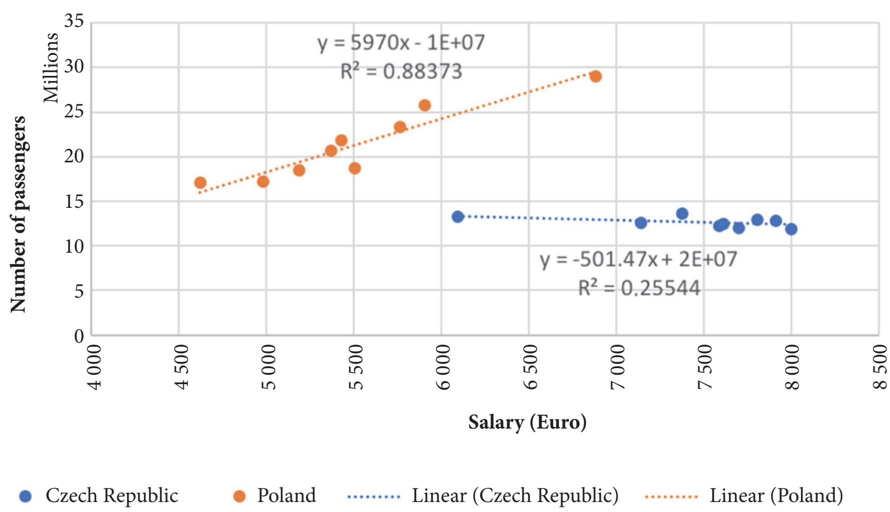

FIGURE 4: Salary over the years in the Czech Republic and Poland. Linear function is presented to guide the eyes.

TABLE 2: Matrix of dependencies between selected countries.

Country	Austria	Belgium	Czech Republic	Finland	Poland
Austria	1	**0.92**	-0.25	**0.97**	0.90
Belgium	**0.92**	1	-0.24	**0.93**	**0.99**
Czech Republic	-0.25	-0.24	1	-0.26	-0.16
Finland	**0.97**	**0.93**	-0.26	1	**0.91**
Poland	0.90	**0.99**	-0.16	**0.91**	1

their own and pay for every single hour. Even then, it takes at least 2 years. In the Czech Republic, there is a possibility to study at the Faculty of Transportation Sciences at the Czech Technical University in Prague. It is a bachelor study program and it takes 3 years. Another possibility is to study at the University of Defence in Brno; however it is dedicated only for military pilots. Nevertheless, some continue their career as airline pilots after completing military service.

Other requirements that may occur in relation to the expected growth of demand for air transport are demands for a trained crew, aircraft maintenance workers, and other related professions. These are such specific professions that a sufficient number of "free" workers of such professions cannot be found on the labour market. Therefore, it is necessary to be aware of this need and start planning the education and training well in advance.

The increase of requirements of air travel brings along not only increased requirements of a trained personnel, but also technical equipment, i.e., the number of aircrafts. With regard to the fact that ordering and production of an aeroplane are very costly and time-consuming, it is another reason for conducting statistical research, market mapping, and observing trends of market development.

In transport analysis, the term "reliability" usually means punctuality [13–16] but for the purpose of this analysis it has been redefined. Based on the number of passages, the number of passengers expected in the near future can be predicted.

Table 3: Rate of change in the analyzed countries in 2004–2016.

Country	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Average rate of change%
Austria	1.000	1.070	1.127	1.235	1.288	1.177	1.268	1.352	1.395	1.381	1.421	1.443	1.464	3.40
Belgium	1.000	1.020	1.098	1.196	1.271	1.236	1.311	1.445	1.490	1.514	1.656	1.784	1.719	5.40
Czech Republic	1.000	1.119	1.214	1.307	1.344	1.238	1.224	1.263	1.175	1.185	1.203	1.276	1.362	2.60
Finland	1.000	1.045	1.139	1.233	1.269	1.182	1.220	1.406	1.411	1.419	1.471	1.494	1.547	3.70
Poland	1.000	1.162	2.224	2.816	3.075	2.806	3.026	3.394	3.590	3.825	4.226	4.756	5.309	14.9

Table 4: Number of passengers as related to salary. The analysis is based on the Eurostat data.

							Poland						
2004	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Number of passengers (millions)	6	7	13	17	19	17	18	21	22	23	26	29	32
Area (km^2)							312 679						
Number of citizens (millions)							38						
Number of tourists (millions)	9	10	10	11	10	10	10	11	12	12	13	14	15
Number of passengers per area	19	23	43	55	59	55	59	66	70	75	82	93	103
Number of passengers per citizens	0,2	0,2	0,4	0,5	0,5	0,5	0,5	0,5	0,6	0,6	0,7	0,8	0,9
							Czech Republic						
Number of passengers (millions)	10	11	12	13	14	13	12	13	12	12	12	13	14
Area (km^2)							78 866						
Number of citizens (millions)							10						
Number of tourists (millions)	19	19	20	21	20	18	18	19	22	22	22	23	24
Number of passengers per area	129	144	156	168	173	159	157	163	151	153	155	164	175
Number of passengers per citizens	1,0	1,1	1,2	1,3	1,3	1,2	1,1	1,2	1,1	1,1	1,1	1,2	1,3

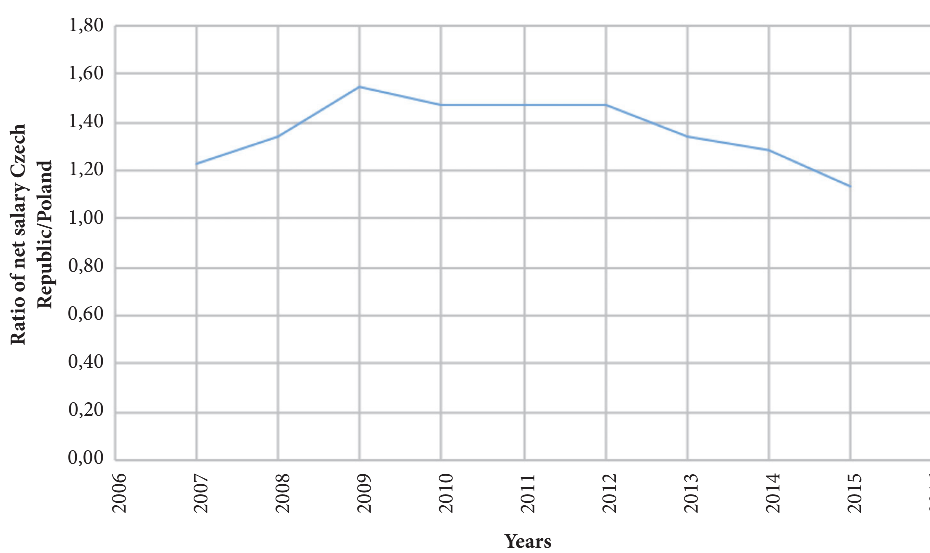

Figure 5: Ratio of net salary in the Czech Republic and in Poland.

This article was mainly focused on two countries, both belonging to the EU and being neighbouring countries. Nevertheless, the performed analysis showed different results.

If the rate of change remains on the current level within 5 years, it can be expected that the number of passengers in Poland will increase up to 44 million. This means that not only a larger crew, but also more aircraft will be necessary. The forecast of air traffic presented by the Civil Aviation Office in 2017 shows that, in 2035, over 94 million passengers will be transported at the Polish airports, almost three times more than in 2016. According to the experts from the Civil Aviation Office, Poland makes up for the distance to the Western European markets which is why further growth is expected in subsequent years [17].

On the other hand, increasing expectations are not so high in the Czech Republic. This is the consequence of the transport policy, published by the Ministry of Transport in June 2013 which suggests shifting 50% of medium and long-distance freight transport from the road to the rail and waterborne transport and, in the case of passenger transport, significantly raising the proportion of rail transport (also moving away from air transport in distances under 1,000 km, making room to air transport for long-distance flights [17].

Data Availability

All used data are from publicly available and quoted sources.

Conflicts of Interest

The authors declare that there are no conflicts of interest concerning the publication of this paper.

Acknowledgments

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Research Article

Urban Transformation in the Context of Rail Transport Development: The Case of a Newly Built Railway Line in Gdańsk (Poland)

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Development of railway transport systems is perceived as one of the most effective ways of shaping sustainable urban transportation. However, railway transportation systems can only compete with individual means of transportation when having properly developed infrastructure, especially in terms of the train stops accessibility. The main objective of this article is to discuss mutual relations between operation of a newly built railway line and spatial changes taking place in its closest vicinity which determine the accessibility to it. The research methods included the GIS tools, direct measurements of passenger exchange, and public opinion poll among the passengers taking the new line. The research area was the city of Gdańsk, one of the largest cities in Poland, where transportation problems are cumulating as a result of the urban sprawl. The new railway was opened in order to mitigate these problems. The research results have proved this strategy was only partially successful as the course of the line and location of the stops do not provide a large number of potential passengers. That is why it was necessary to connect the line to the already existing urban transportation system, yet this solution has not resolved the problem completely. However, the urban development plan assumes introduction of large housing projects in the areas surrounding the existing train stops what will allow using the new line more efficiently in the future.

1. Introduction

Transport is regarded as a basic factor fostering development of urban regions [1–3]. The "triumph of the city" [4] will not be possible without an efficient transportation system, urbanisation, although in some regions it is not as dynamic as it used to be in the demographic aspect, it is still progressing in the economic, social, and spatial dimension. The structure of urban transportation systems is subject to ongoing changes. Pedestrian traffic and public transport are considered to no longer have a dominant position in the system; motorised individual transport is now the most important part of it. The external costs of such a model (including costs of accidents, air pollution, climate change, noise, and congestion) [5] have forced search and implementation of solutions aimed at supporting pedestrian traffic, improving public transportation systems and promoting alternative ways of individual transport (private bicycles, urban bicycles, car-sharing systems, and all kinds of electric individual means of transport). Although, obviously, technological progress was the main force driving the above-mentioned changes [6], yet some social phenomena were also fostering them, such as emergence of the automobility culture [7] and the concept of sustainable mobility, aimed at overthrowing the car culture. In order to introduce the idea of sustainable mobility, actions in four basic dimensions have to be taken: implementing the latest technology to increase the efficiency, developing a pricing policy which internalises the external costs generated by each and every mode of transport, introducing spatial management tools aimed at decreasing in demand for transport and bringing about a change in the modal split, and providing a precisely addressed information system for citizens [8].

One way of bringing the idea of urban sustainable mobility into life is to develop rail-based public transportation systems, including urban railways. Such systems allow increasing efficiency of transport in two ways: through technical improvement of infrastructure and vehicles and,

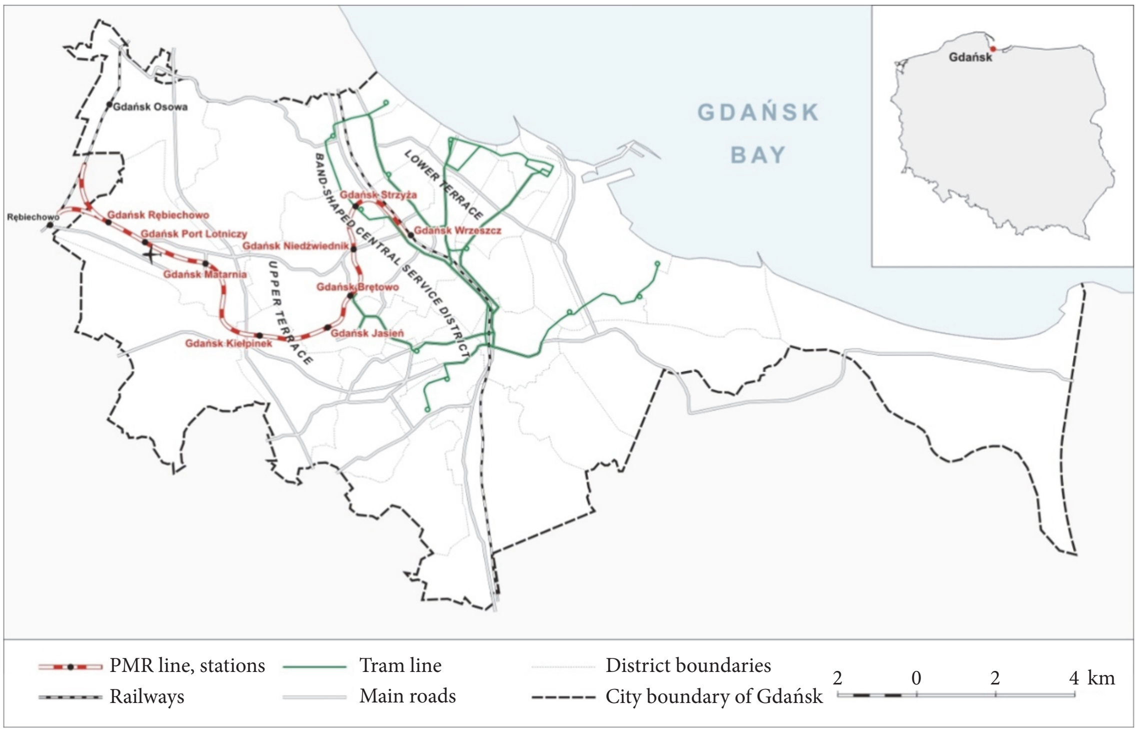

Figure 1: The Pomeranian Metropolitan Railway line within the city of Gdańsk boundaries.

above all, through introducing a change in the modal split which limits use of private cars and reduces congestion and its all negative consequences, including the social ones [9]. This change is also vital in the context of reducing greenhouse gas emissions [10]. Everyday functioning of cities and transportation systems is extremely energy-consuming; that is why the potential of reducing the emissions is so high in this case. However, these benefits can only be achieved when development of public rail-based transport systems is coupled with proper spatial planning. Hence, rail-based transport plays a valuable role in shaping the spatial-functional structure of cities [11, 12].

In the postsocial countries, including Poland, the presented above sequence of transformations took place much later. The system transformation towards the free-market capitalism (after 1989) covered both transportation and city management, to some extent. Not sufficient, in relation to actual demand, expenditures on the public transport infrastructure led to its degradation. Only some components of the system have been privatised, often with foreign capital participation, yet it has not improved the transport offer on a national level [13]. The rest of it, especially local commuter bus and train lines, have been gradually dismantled. This regression in the number of local lines was one of the main reasons for the decrease in the rail passenger traffic [14]. According to the data published by the Central Statistical Office, in 2000 the number of rail passengers in Poland constituted only 48% of the number recorded in 1990 and the number of bus passengers, 60%. At the same time, the number of private cars constituted 189% of the number recorded at the beginning of the analysed decade [15]. A significant increase in the level of motorisation was not only a result of the regression in the public transportation services. Owning a car was a factor shaping the way of life and it served as a status symbol [16]. During the next decade after the beginning of the transformation (2000-2010) there were no significant changes in the structure of the above-mentioned modes. Accession to the European Union in 2004 allowed using the Structural Funds for development and modernisation of the transport infrastructure. Some of the money was set aside for development of urban road networks, what made it possible to reduce the traffic congestion in large cities, at least temporarily [17]. There were also some funds allocated for development of railways, including urban ones, but the scale of investment was less significant. Railway systems of Warsaw, Gdańsk-Gdynia-Sopot, Lodz, and Cracow were modernised at that time [18].

The main objective of this article is to answer a question to what extent launching the Pomeranian Metropolitan Railway has contributed to changes in the spatial and functional structure of Gdańsk, one of the largest cities in Poland (see Figure 1). E. Babalik [19] arguments the urban form of cities can influence the success of urban rail systems. It was observed that the economic vitality of central business districts, the location of employment and retail outlets, the population and residential density, and the dominant urban pattern were particularly important. Taking the strategic value of this investment under consideration, the authors will also make an attempt to indicate possible directions of spatial development of the city during the next decade. Transportation systems affect the process of spatial and functional urban structure shaping. That is why, in this article, a case of the Pomeranian Metropolitan Railway and the way it influences the urban structure of Gdańsk will be described, along with the mobility patterns of its citizens.

Despite the fact that the Pomeranian Metropolitan Railway serves other towns in the region, the spatial scope of this article is limited to the city of Gdańsk, where the main investment efforts were concentrated. Special attention was paid to the areas located in the closest vicinity of the PMR stations as the most notable changes in the spatial and functional urban structure can be observed there. The areas are planned to undergo some far-reaching changes in terms of spatial development. The time scope of the analysis was three years of the PMR operation, that is, from mid-2015 to mid-2018. However, the future plans for further development of the Pomeranian Metropolitan Railway as well as provisions of the spatial development plan for Gdańsk have also been analysed [20].

The article consists of four parts. The first one comprises general background information on the case study, including information on the investment circumstances, the course of the route, location of the stations, and the size of passenger flows. In the second part the authors indicate the research methods and sources of the data used for analysis. The results have been presented with attention paid to four major issues: the existing land use patterns, population density, the degree of linkage between the PMR and the bus and tram systems, and expected changes in the land use. The article is completed with conclusions and recommendation concerning further research tasks.

2. Case Study

2.1. Unsustainable Mobility: Gdańsk as Typical Case of Polish Large City. Gdańsk is the sixth largest city in Poland with a population of approximately 464 thousand people (2016). Along with Gdynia and Sopot the three cities comprise a band-shaped spatial layout of a polycentric structure, which emerged as a result of many interrelated environmental, social, economic, and political conditions. It is a centre of a large urban region with a population of approximately 1 million people. According to the typology of functional urban areas created on the basis of their size, competitiveness, knowledge sources, and their accessibility [22], this region belongs to Type 4 European metropolitan areas as well as Szczecin, Poznan, Wroclaw, Lodz, Cracow, and Katowice (in Poland) and Cork in Ireland, Southampton (along with Bournemouth and Portsmouth) in Great Britain, Porto in Portugal, Seville in Spain, Havre and Bordeaux in France, Genoa in Italy, Valletta in Malta, Turku in Finland, Tallinn in Estonia, Riga in Latvia, Vilnius in Lithuania, Bucharest and Timisoara in Romania, Sofia in Bulgaria, and Ljubljana in Slovenia. Gdańsk, as well as other large Polish cities, faces the problem of unsustainable mobility. According to Gdańsk Traffic Research [23], the share of individual transport is 41% and it significantly exceeds shares of other forms of mobility. However, such a structure of urban traffic is not something unusual; it is commonly observed in other Polish and European cities. There are also cities with a higher share of individual transport yet it does not change the fact that the modal split of transport based on individual means of transportation causes a number of essential problems in terms of functioning of cities and everyday life of their citizens. One of the most recognisable one is traffic congestion. As it has already been mentioned, this phenomenon has been developing in Poland since the beginning of the political transformation and nowadays it has reached the level observed in the highly developed countries. Not only was it a result of a general improvement of the citizens' wealth, but also it is connected with chaotic development of suburbanisation.

2.2. Local Context of Urban Mobility in Gdańsk. All the above-mentioned general problems affect Gdańsk, yet there are some local factors influencing the situation, too. The environmental conditions were the main reason why the city has band-shaped infrastructural systems serving two relatively separated parts of the city: the lower terrace, located mostly on an alluvial plain (northern and eastern parts of Gdańsk) and the upper terrace, located at 100-150 m above sea level, on a postglacial upland (southwestern and western parts of Gdańsk). On the lower terrace there is a historical city centre, band-shaped central service district, port and industrial areas, and residential districts with high population densities. On the upper terrace there are mainly scattered residential areas of lower population densities. They generate problems for public transportation system and are not as well communicated as the central ones. On the upper terrace there are also several other objects generating traffic: the airport with an industrial district nearby and some large shopping centres. A steep edge of the upland is a natural boundary separating the two parts of the city. It is covered with forest and it is legally protected. As seen from the perspective of urban development, this barrier was overcome in the 1970s and 1980s when large-panel prefabricated housing estates were built. The process of inhabiting the upper terrace was continued during the period of transformation. It showed signs of chaotic internal suburbanisation [24]; there were both detached houses built by the owners themselves and large residential areas constructed by developers. Such a suburbanisation model makes it difficult to make urban mobility sustainable. Modernisation and development of the road system on the upper terrace began too late and its pace was not sufficient. As for the public transport infrastructure, the situation was even worse and it did not contribute to a decrease in the share of citizens using private cars. On the contrary, the role of this means of transport increased by 2% when compared with 2009; the city has not been moving towards the sustainable mobility model [23]. However, some adverse trends had been noticed before that and they triggered an intense public debate regarding further transport investments in the city. The conclusions of this debate were included in the Gdańsk 2030 Plus Development Strategy [25]. As for transport and mobility it was stated that the modal split of transport in the city has to be changed in order to meet the criteria of sustainable mobility. The Pomeranian Metropolitan Railway had already been under construction at that time and it was considered a logical component of this plan.

2.3. Towards More Sustainable Mobility: Pomeranian Metropolitan Railway. Construction of an agglomeration railway line in the urban area of Gdańsk-Gdynia-Sopot has been planned for several decades. It was assumed that the railway line would connect the city centres of Gdańsk and Gdynia with the existing airport in Gdańsk and the planned one in Gdynia-Kosakowo. It was planned to extend the offer of the Fast Urban Railway running along the central service district. Initially, it was assumed that the PMR would start operation before the 2012 UEFA European Championship, but it was not possible to meet the deadline. It took three more years to complete the construction. The Pomeranian Metropolitan Railway is a name for the line itself and for a special purpose company established to construct and then manage the railway line. The line was constructed between 2013 and 2015, financed mainly from the structural EU funds. Although it was built along an old railway line, which was there in the past, the whole infrastructure had to be reconstructed. That is why this investment is of special meaning as there was no other urban region where the scale of construction and modernisation of a railway line was that large.

As part of the investment, a railway line (19,5 km), including 18 km of a double track section towards Gdańsk-Osowa station and a connector (1,5 km), was constructed. Additionally, eight new stations were built and two more already existing ones were modernised to connect the PMR with the Fast Urban Railway. The maximum permissible speed on this route is 120 km/h.

Right after launching the PMR the line Gdańsk Główny–Gdańsk Airport–Gdynia Główna started to operate as well as two shorter lines to Gdańsk Osowa and Gdańsk Wrzeszcz. Then, in the period of 2015-2016 other two lines were opened connecting Gdańsk with two smaller towns located outside the urban area. However, in this article, the main focus will be put on the lines located within the city of Gdańsk boundaries.

A relatively short, three-year period of the PMR operation, during which there were numerous changes in the timetable as well as a temporary cessation of operations due to extremely heavy rain in July and August 2016, does not allow unambiguously evaluating the investment. An actual impact of the Pomeranian Metropolitan Railway on the urban traffic may be assessed by analysing the number of its passengers (Figure 2). In the period of October 2015–March 2018 a visible positive trend is observed when analysing the total number of passengers. However, when analysing the number of passengers using not only the innercity lines, but also the ones connecting Tricity with Kartuzy and Kościerzyna, some interesting patterns can be observed. According to the PKM S.A. (PMR limited company) data, the number of passengers taking part in the metropolitan traffic (Gdańsk and Gdynia) actually decreased from 151,6 thousand in June 2016 to 141,1 thousand in June 2017. Most probably, thanks to modifications in the timetable it was possible to reverse this negative trend and in March 2018 the number of passengers reached approximately 190 thousands.

The results of a direct measurement carried out in the period of October-November 2017 [21] have shown that the most popular stations in Gdańsk are Wrzeszcz, Strzyża, and Jasień. Airport and Kiełpinek are also among the stations of

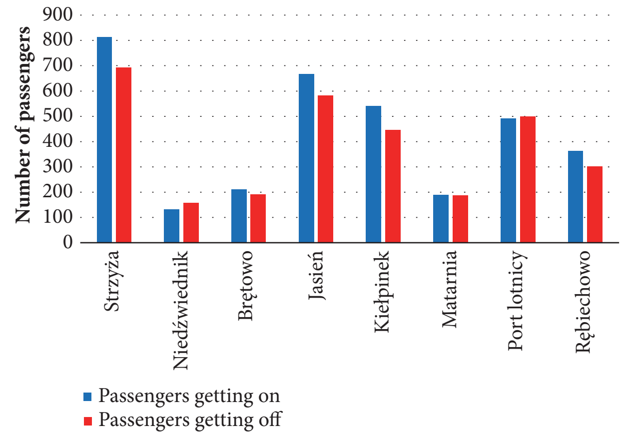

Figure 2: Average daily number of getting on and getting off passengers by the PMR line stations in the period of 17.10-16.11.2017. Source: own elaboration based on [21].

significant importance. The least popular among the PKR passengers is Niedźwiednik station. It is situated relatively close to the central service district and it is more convenient for the citizens to reach it by bus.

3. Methods and Data

In order to achieve the objective of this article the authors used a whole range of GIS tools; they carried out direct measurements of the passengers flow and they interviewed the passengers using the PMR service.

3.1. GIS Tools. The GIS tools (QGIS software) were used while determining spatial conditions along the railway line, location of the stations, and how they are connected by bus and tram. The GIS tools were also useful when describing the foreseen changes in the land use. The base for their implementation was a map of topographic objects at 1:10 000 scale obtained from a publicly accessible cartographic resource base.

In order to assess the land use character and intensity of development in the closest vicinity of the stations, a tool named “fixed width buffer” was used. It allowed delimiting a 660 m equidistant for a 10 minutes’ walking distance and a 1320 m equidistant for a 20 minutes’ walking distance to the stations being central points of the delimited zones (Figure 3). The 660 m equidistant was also used to delimit the zones of 10 minutes’ walking distance to the bus or tram stops which allow reaching a given PMR station within 5 minutes. In the literature normal walking speed varies from 3,2 km/h to 5,4 km/h and 4,5 h/km on average [26]. In order to calculate the distance to the PMR station, which passengers have to cover in the 10- and 20-minute zones, the average normal walking speed of 4km/h was adopted [27–29], taking the space resistance resulting from implementation of the straight-line mechanism under consideration.

Time distances between the stations were calculated on the basis of public transport schemes and timetables for buses and trams published by the urban transport operator. This

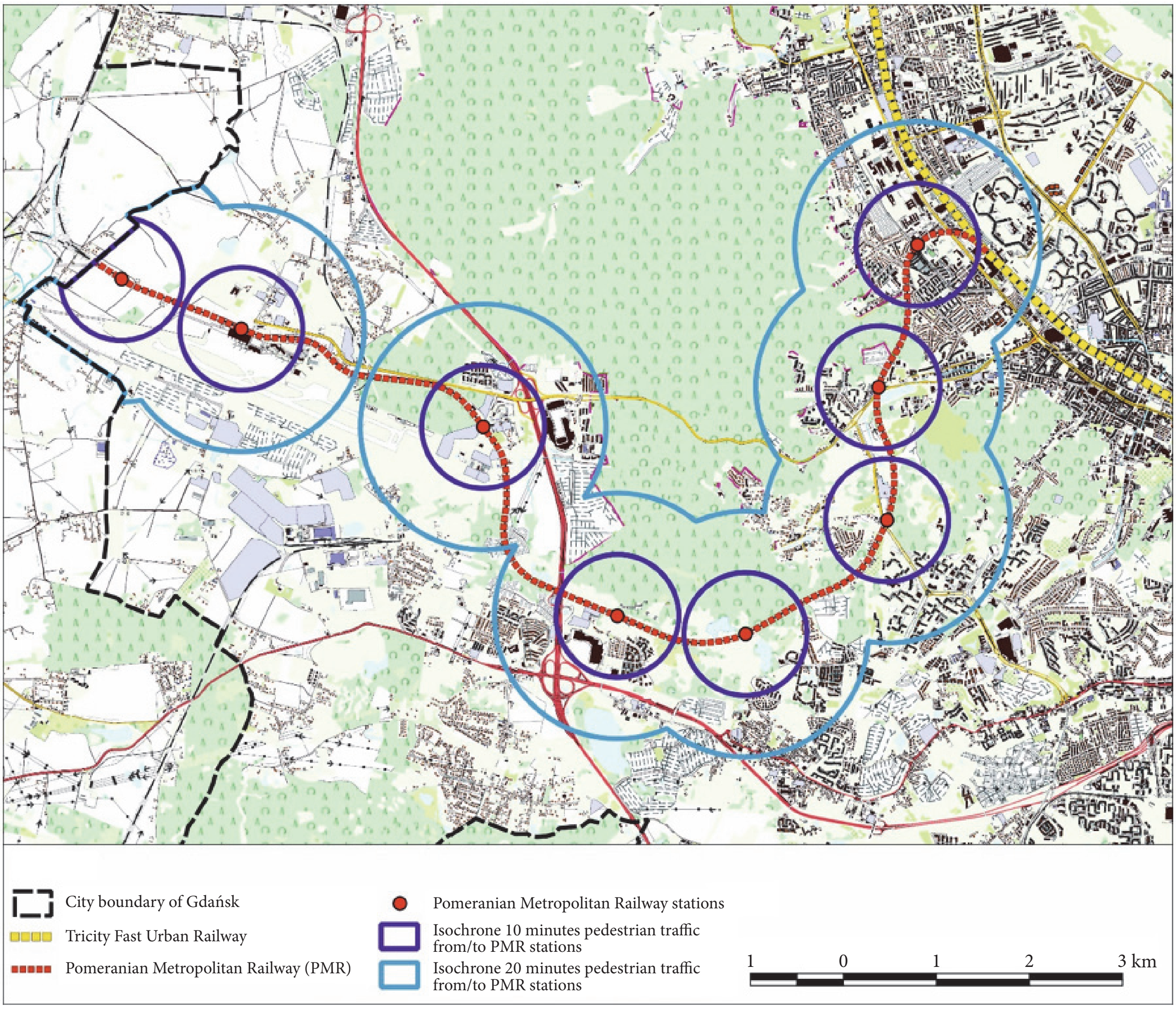

Figure 3: Zones of 10-minute and 20-minute walking accessibility to the PMR line in the context of the contemporary land use forms.

procedure allowed delimiting an indicative intermodal which is served by the PMR, buses, and trams (Figure 6). Intensity of communication linkages between the railway stations and bus/tram stops was depicted with the use of a ribbon-like cartogram. It was created on the basis of the timetables, taking the average number of all 5-minute daytime bus and tram courses to/from the railway stations on weekdays during a school year (both directions) (Figure 6). In order to assess the character and intensity of land use in the whole area served by the PMR, the authors analysed population density grids (100 m/1ha). The most recent data on number of people registered in the city of Gdańsk at the end of 2016 was obtained from Gdańsk Development Office, local authority responsible for the spatial policy. In Poland it is obligatory for all citizens to register. However, there are no sanctions forcing people to do so. The majority of population actually lives in places where they are registered yet the number of people who do not is still growing. In 2009 the data regarding the number of registered people was officially published for the last time; in Gdańsk it was lower by 1,1% than the number assessed using the balance sheet method. Using the above-mentioned data, the number of people having access to each railway station, the number of people living in common areas of the 1320 equidistant zones, and the total sum for all the stations were calculated. When calculating, rectangles having their geometrical centres within a zone set by a particular equidistant delimited for each of the station (Figure 5) were taken under consideration. Additionally, in order to assess the current land use structure as well as the planned changes in it, cartographic data included in the general local development plan for Gdańsk was used [8]. On the maps, being attachments to the plan, dominating land use forms, housing and housing-service areas as well as the foreseen changes in the land use are presented (Figure 7).

3.2. Passenger Traffic Measurement and Questionnaire Survey. In order to assess the volume of passenger traffic at every PMR station and the impact that the PMR exerts

Table 1: Land use forms in the closest vicinity of (660 m radius) the PMR stations in Gdańsk (at the end of July 2017.

Station	Dominating housing development type	Dominating land-use forms – housing and housing-services (ha)	Dominating supra-local service or industrial functions	Elements integrating the station with other modes of transport
Strzyża	mixed with a domination of single-house	39	university campus, tram depot, shopping centre, sports centre, car showrooms,	tram stop at the depot and a regular tram stop
Niedźwiednik	multi-house	28	asylum, cemetery, non-public schools	bus stop
Brętowo	mixed	40		terminal tram stop and a bus stop
Jasień	multi-house	14		terminal bus stop, car park
Kiełpinek	mixed with a domination of multi-house	17	shopping centre	terminal bus stop, car park
Matarnia	multi-house	11	service and industrial companies	bus stop, car park
Port Lotniczy	scattered single-house	3	office buildings, hotel	airport, terminal bus stop
Rębiechowo	scattered single-house	3	arable lands	

Source: own elaboration based on the GIS analysis and fieldwork.

on mobility patterns, data on the volume of the passenger traffic was used [21]. The data was obtained during the 17.10.2017-16.11.2017 measurements carried out on typical weekdays in two sessions (6:00-9:00 and 14:00-19:00). For three selected stations 16-hour measurement was carried out. The measuring staff encompassed well-trained observers equipped with measuring cards, documents with a detailed description of the measurement, visibility vests, and name badges. Moreover, the passengers were being interviewed with the use of a standardised questionnaire. They were asked about motives behind and frequency of their journeys, why they choose the PMR, how they get to a starting station, and how they continue their journey after getting off the train. Usually, there were from 1 to 3 interviewers on each station, depending on where a given station is situated and the estimated number of passengers using it. The report summarising this measurement is publicly accessible and it was obtained from the Pomeranian Regional Planning Office which had commissioned the research. The office is regional authority responsible for the spatial policy.

4. Results and Discussion

4.1. Land Use Zones in the Areas Surrounding the PMR Line. The main problem connected with reconstructing an old railway line is the fact that the areas it used to cover have been built-up and now they are potential sources of passenger traffic. This is also the issue affecting the Pomeranian Metropolitan Railway line. Only two stations, Wrzeszcz and Strzyża, located on the lower terrace within the central service district are situated in a highly urbanised area with well-developed housing, service, and communication functions (Table 1). Other two stations, Niedźwiednik and Brętowo, are located in the upland edge; thus there are not many housing or service areas in their closest vicinity, yet still within the range of the 660 m zone. In most cases, in order to reach the station people have to walk up/down a steep hill what may discourage them from using the PMR trains.

There are five stations located in the upper terrace. The closest vicinity of three of them, Jasień, Kiełpinek, and Rębiechowo, is not densely built-up. In the areas around Jasień and Kiełpinek new housing estates are being constructed; some of them have already been finished. The areas around Kiełpinek station are the most densely built-up. There is a large housing estate there and a large shopping centre. However, the station is not located in the centre of this area so it is not attractive for all its residents. The least densely built-up areas surround Rębiechowo station (Table 1, Figure 3); they are mainly arable lands and areas with highly dispersed single-housing development; additionally, most of it is not located within the city boundary. The station is located near the city boundary in Banino, a village being now under a severe suburbanisation pressure.

The areas surrounding Matarnia and Port Lotniczy stations are more densely built-up than the closest vicinity of the three previously described stations. Matarnia station is located on the edge of a large industrial district and a housing estate. Such a peripheral location of this station marginalises its role in transport services. The second station (Port Lotniczy) is located near the airport which is a key object for this railway line. Improving accessibility of the airport was one of the motives behind the construction of the PMR line. What is more, in this area there are airport car parks, a hotel, and some objects situated on the edge of an office district, which core, in a form of the "Intel" headquarters, is not in the zone of convenient accessibility to the station.

The analysis of the land use of areas surrounding the PMR stations has confirmed a strategic character of this investment. It may be stated that it partially exceeds the foreseen demand what is a rare situation in Poland. However, the true future role of the PMR will depend on the housing estates

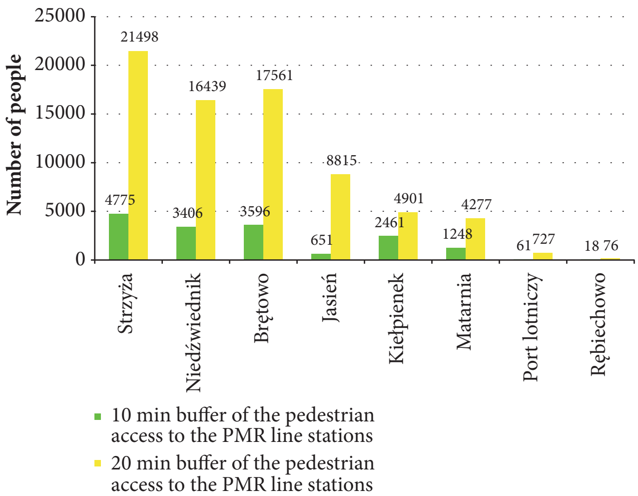

Figure 4: Population density in the zones of 10-minute and 20-minute walking accessibility to the PMR stations.

development, organisation of bus and tram transportation systems, and their coordination as well as on development of the park and ride system in the vicinity of the line.

4.2. Population Density in the PMR Line Impact Zone. Spatial distribution of population is a consequence of the above-described course of the PMR line and the intensity of land use. Population density is a vital factor affecting the level of its success, the success understood as a volume of passenger traffic [30]. For the purposes of this study, population densities for the 10-minute (660 m) and 20-minute (1320 m) walking accessibility zones have been calculated using the registration data. Areas located nearer to the Pomeranian Metropolitan Railway stations have low population densities reaching 15 people per 1 ha on average. The population densities vary from 0,16 ppl/ha for Rębiechowo station to 34 ppl/ha for Strzyża station. The highest number of people living within the 10-minute (660 m) and 20-minute (1320 m) walking accessibility zones was recorded for Strzyża station, 4,8 thousands and 21,5 thousands, respectively. The lowest number for Rębiechowo station was only 18 and 76 people, respectively (see Figures 4 and 5).

Population density in the Pomeranian Metropolitan Railway impact zone is relatively low. The line has been located on the edge between some green areas (the landscape park) and new housing estates where developers started constructing buildings during the last decade. As an effect, the largest impact on effectiveness of the PMR line should be exerted by redirecting the vehicles of public urban transport to serve the railway stations in a formula of the multimodal transport (In the article the term "multimodal transport system" refers to a partially integrated transport system as the system in the city of Gdańsk is not fully integrated. There is no one official body managing all different transport subsystems. There is only a partially integrated fee system. Among the main tasks related to exploitation of the PMR line is integrating the public urban transportation system in Gdańsk and the PMR stations. Such actions refer to the idea of multimodal transport. In the literature, the issues of multimodality in everyday commuting have not been frequently addressed so far [31]. In a review article entitled *Rail and Multimodal Transport*[32] there are eighteen definitions, but only two of them refer to passenger transport. In both cases, by W. Jones et al. [33], it is defined as using two or more means of transport during one integrated journey. In passenger transport, the level of multimodality depends less on accessibility of alternative transport links, yet more on the quality of them, including presence of interchanges. In the literature, this quality is known as interconnectivity [[31] after: [34–36]]. Strategic documents issued by the European Union similarly define the way of organising urban transportation systems. In the White Paper "Roadmap to a Single European Transport Area–Towards a Competitive and Resource Efficient Transport System" [37] a vision of development of the European transport system by 2050 and a strategy of achieving the objectives were presented [38]. According to this document, one of the most important problems of European cities is traffic congestion, bad air condition, and the noise. Reorganising the transportation system in a way which will allow using the multimodality more effectively may diminish negatively its impact on the living environment [35, 39]). Development of proper infrastructure (park&ride, kiss&ride, and urban bike systems) serving individual means of transport (cars, mopeds, and bicycles) in the closest vicinity of the PMR station is also of great importance.

4.3. The PMR Line as a Part of a Multimodal Transport System. Effective organisation of urban public transport, especially in metropolitan areas, relates to its full integration and high-quality services. Transportation systems in large cities usually comprise several different modes of transport. Gdańsk is an example of such a situation having bus and tram lines, Tricity Fast Urban Railway and the Pomeranian Metropolitan Railway line, which is the main subject of this article. Full integration of all these modes is difficult as particular modes are owned and managed by different bodies and financed under different regulations. However, when taking the objectives behind constructing the PMR line and high costs of its construction under consideration, cooperation of the bodies responsible for managing and organising the public transportation system shall be the number one priority.

During the period of preparations before launching the Pomeranian Metropolitan Railway the body responsible for managing the urban transportation system in Gdańsk, Zarząd Transportu Miejskiego (Public Transport Council), prepared a plan of necessary changes which should have been introduced to the already existing bus and tram route network. The main assumption of this plan was to reconfigure the routes so they complement each other. It was planned to liquidate the bus lines connecting areas surrounding the PMR stations with the city centre, reorganise ten lines in order to connect them with these stations, and turn them into feeder lines as well as creating a new feeder line. Thanks to these solutions people living in areas remote from the PMR line could access the stations more easily which may result in a larger number of passengers using the public transportation

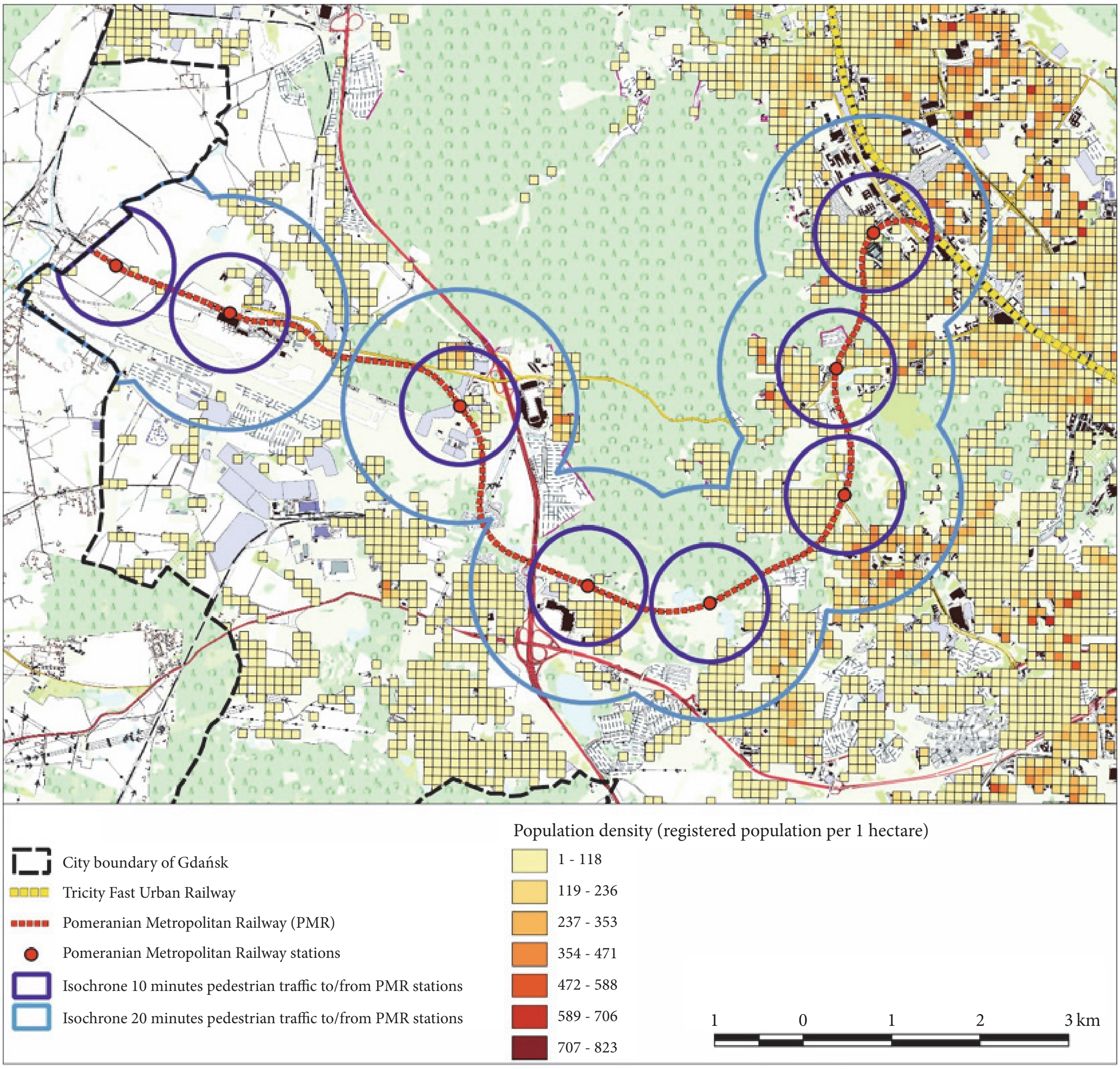

Figure 5: Population density per 1 ha in the zones of 10 and 20-min walking access to the PMR stations.

system. The main objective of the authorities was to reduce competition between the constructed railway and the existing bus and tram lines. Nonetheless, after launching the PMR line not many changes were introduced to the already existing bus and tram route network. At that time the authorities stated they had to assess the level of the citizens' interest in using the new railway first and then introduce the changes, however, not so rapidly. All in all, it is not an approach fostering the idea of sustainable urban mobility. Obviously, the higher the possibility of a quick and comfortable change, the higher the level of interest in a railway line situated far away from their homes. A multimodal journey may be attractive to the citizens when it is faster than using a single means of transport.

Most of the changes which were actually introduced, when the PMR line was launched, regarded the tram lines as a route extension had been built to Brętowo stop. Thus, a possibility of a door-to-door change between the trams and the PMR trains has been created, especially attractive to the citizens living in Morena housing estate. The extension provides tram services every ten minutes in the rush hours. Some routes of the bus lines have also been modified. There were two integrating hubs constructed near Jasień and Kiepinek stations. The bus stop near Matarnia station has not been liquidated and still two lines stops at it. As for the PMR station located near the airport there were no changes introduced, all three lines stops at it. In Osowa district all the bus lines remained unchanged, too.

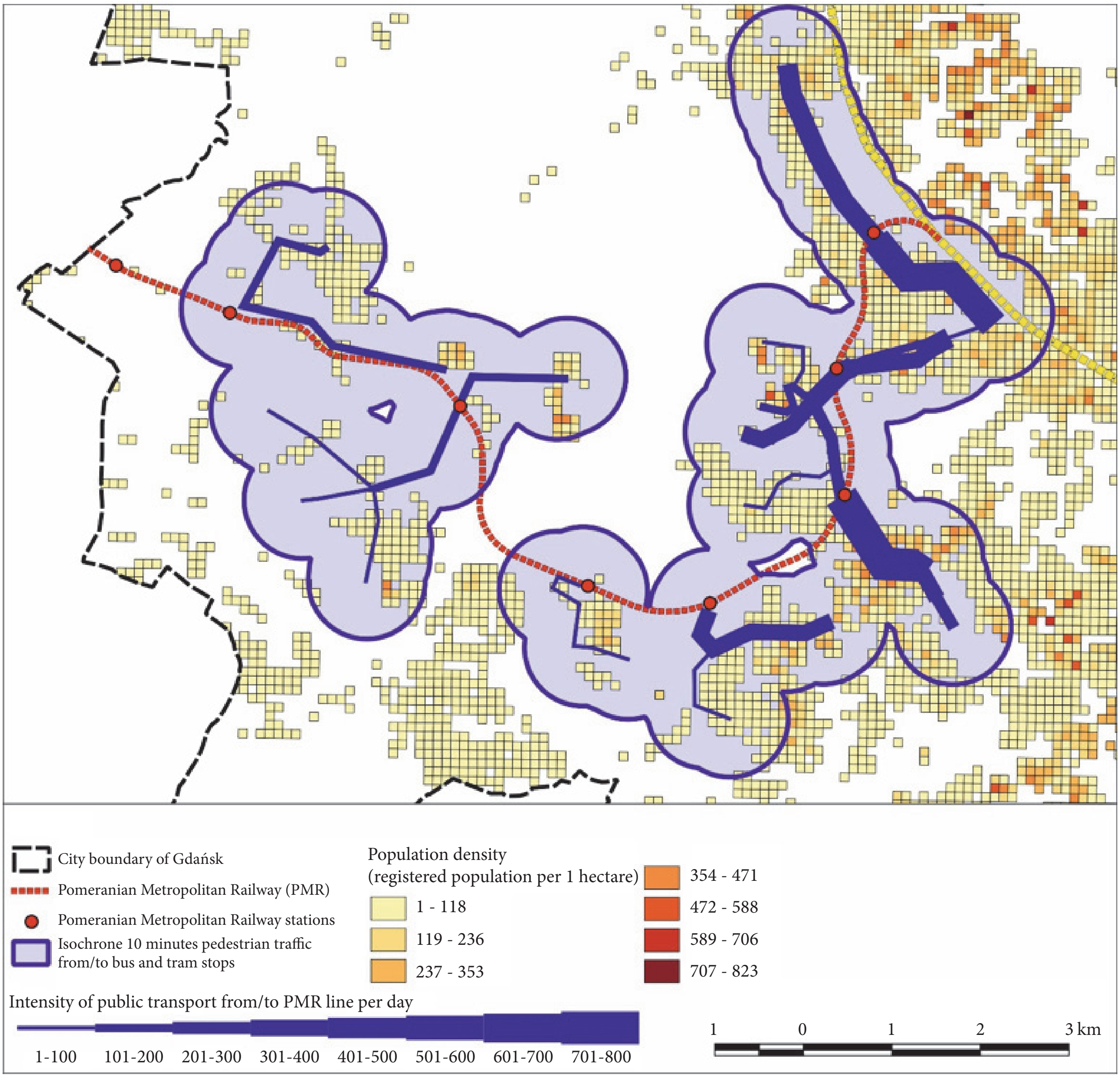

FIGURE 6: Supply of the bus and tram transport services in a multimodal connections model (the number of operations per day).

Launching the Pomeranian Metropolitan Railway line has forced the authorities to reorganise that part of the urban transport system which served the areas surrounding the line. Two integrating hubs (near Kiełpino and Jasień stations) and a tram line extension to Brętowo station were built; all the projects were cofinanced by the European Union. Although these new infrastructural investments were very important for the transportation system of Gdańsk, they did not liquidate the problem of competition between different means of transport. However, the most significant disadvantage of the new transportation system is lack of tariff integration due to different bodies managing the systems. The one and only common metropolitan ticket is distributed by the Metropolitan Public Transport Association of Gdańsk Bay yet this solution is quite expensive and not popular among the citizens [40].

For the purposes of this study the authors analysed the supply of bus and tram transport services which may be incorporated into multimodal lines to/from the PMR stations (see Figure 6).

Approximately 84 thousand people live within the zone of 10-minute walking accessibility to the nearest bus or tram stop allowing to reach the nearest PMR station in 5 minutes. Figure 6 presents possibilities of change between the PMR stations and the bus/tram stations. Strzyża station has the best accessibility of all as there is a tram line nearby. Because the trams are faster than the buses more citizens can change at this station. Brętowo is another station where

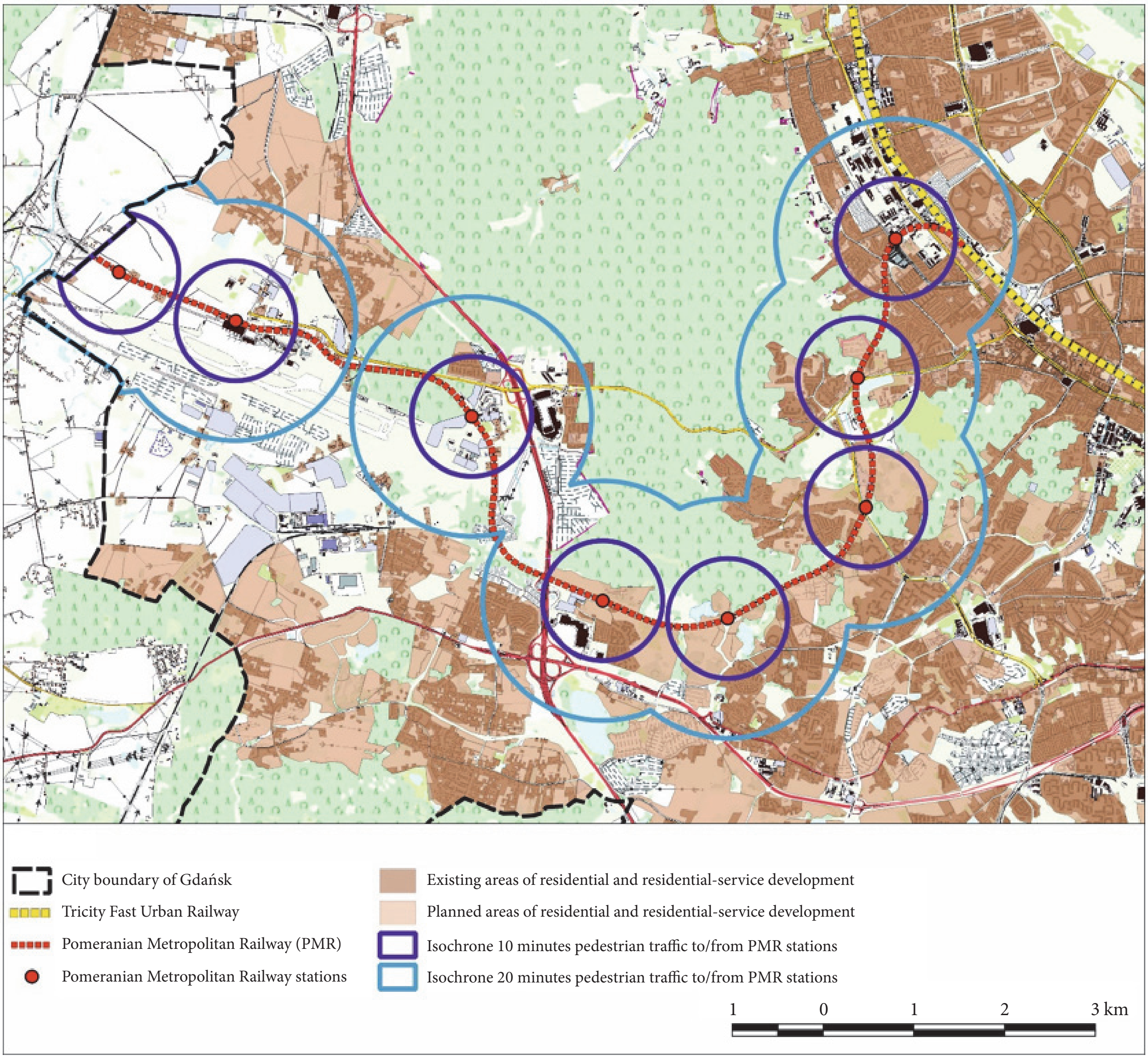

Figure 7: Directions and perspectives for development of different land use forms in the area of 10 and 20 min walking access to the PMR station.

it is possible to organise tram-train services. The supply of transport services has been evaluated as very high, which is essential in the context of population density and type of building development in the PMR impact zone (multifamily buildings, 10-storey block of flats).

The potential of changing the modal split towards the sustainable mobility model can also be assessed by analysing the ways in which passengers get to the PMR station and continue their journey. The survey outcomes indicate that the passengers usually walk to the PMR stations (48%) (excluding the terminal ones: GdańskWrzeszcz and GdańskOsowa). 16% of the respondents take a bus, 14% drive to the stations (both drivers and passengers), and 11% travel by tram. Such a high percentage of pedestrians, taking the low population density in the areas surrounding the PMR line, indicates the PMR stations are not well-connected by the means of public transport. As for the percentage of passengers driving to the stations, it seems the PMR directly contributes to reducing the car traffic in the city. Moreover, one can suppose that some of the passengers connecting by bus or tram at the moment used to drive, so the positive effect of the PMR operation is even more visible. It can be also assumed that along with an increasing number of the PMR passengers, which is still rather low, the positive impact of the new railway line will be even stronger and the whole transportation system will follow the path towards the sustainable mobility model.

When analysing the ways in which passengers get to the particular stations some significant differences were observed (Table 2). They result from the land use patterns (functions and intensity of development) and transport

Table 2: Main (over 10% share) ways of reaching the PMR stations and continuing the journey, based on the results of a survey conducted between 17.10 and 16.11.2017.

	on foot	tram	bus	car	train	plane
Gdańsk Niedźwiednik	80,5					
Gdańsk Kiełpinek	72,7		10,3	13,9		
Gdańsk Matarnia	57,8			22,9		
Gdańsk Strzyża	52,0	33,0				
Gdańsk Brętowo	45,4	26,2	19,2			
Gdańsk Port Lotniczy	43,2				10,8	30,5
Gdańsk Jasień	31,8		49,8			
Gdańsk Rębiechowo	9,6			58,5	25,9	

Source: own elaboration based on [21].

linkages between the stations and hubs of the urban public transportation system.

Gdańsk Niedźwiednik station, located relatively near some large housing estates, is used mainly by pedestrians. Moreover, this station is situated so close to the central service district that it may be faster to take a bus or travel by bike (in the rush hours). Kiełpinek and Matarnia stations are also located in densely populated areas and near some large shopping centres. Unlike Niedźwiednik station, these are situated on the upper terrace. That is why it is possible that a significant percentage of passengers coming from peripheral districts of Gdańsk or living outside the city reaches those stations by car and then continues their journey by tram to avoid wasting their time in traffic jams. Strzyża, Brętowo, and Jasień stations are the ones which are reached mainly by trams. As for Port Lotniczy station it is most frequently used by air passengers. Rębiechowo station is located in the outskirts of the city in areas of low population density. This is the reason why the percentage of pedestrians is so low and the percentage of drivers is so high. At this station it is also possible to change the railway line.

4.4. Perspectives for Development of Areas Surrounding the PMR Line. As it has already been mentioned, due to the fact that the PMR line has been constructed along the old railway line, some stations are located too far from the main traffic sources. One of the consequences of such a location is the necessity to change the existing land use patterns of areas surrounding the PMR stations. It is what will, most probably, happen in the future. In the newest version of a general plan for spatial development, which was updated due to launching the PMR line [20], the necessity of pursuing the current spatial policy is emphasized and, at the same time, the document indicates the need to change directions of spatial development of the areas surrounding the stations. The areas used to be earmarked for leisure (green areas) and other extensive functions will be earmarked for the housing and services (Table 3, Figures 7 and 8). It is estimated that the housing function will develop in the closest vicinity of Brętowo, Jasień, Kiełpinek, and Niedźwiednik stations. While any new residential buildings constructed in the districts located on the upper terrace shall not be densely packed up and have a high percentage of the biology active surface, in the case of areas surrounding the PMR stations housing estates will be of higher built-up density. In turn, for the areas surrounding Port Lotniczy and Rębiechowo stations it is planned to liquidate the residential function and intensively develop production, service, and logistic functions. In the vicinity of the airport there will be more than 140 ha earmarked for commercial and public investments [20].

The project assumes further integration of Gdańsk urban transportation system and the transportation system of the whole metropolitan region. Here, the PMR line is also of great importance. According to the adapted in the project classification of integrating hubs, Port Lotniczy station is of national, Wrzeszcz station is of regional, and Rębiechowo is of metropolitan significance. Jasień and Brętowo stations have been classified as local integrating hubs. Other stations shall also have integrating significance. What is more, the question whether a new tram line will be launched along the PMR track connecting Strzyża and Brętowo station is still open or will it be possible in the future to share this section of the PMR track, as current legal regulations do not allow such a solution [20]. Moreover, while electrifying the line, a new station (Gdańsk Firoga) is planned to be built. It could increase accessibility to an office centre being a headquarter of the Gdańsk branch of Intel Corporation.

5. Conclusions

During the first decade of political transformation in Poland (after 1989) retrogressive development of public transportation services (road and rail) was observed. At the same time, the role of individual transport (cars) increased significantly. Partially degraded and underdeveloped road infrastructure and the process of urban sprawl in large Polish cities made their citizens face all the negative consequences of living in cities dominated by car traffic.

When Poland became a member of the European Union in 2004 some new opportunities emerged. Financial support of the EU allowed modernising numerous transportation systems although the main focus was put on developing road systems, not railways. In Gdańsk, one of the largest cities in Poland, a completely new, 19,5 km long, railway line was constructed along with eight new stations. Despite the fact that the new line was laid along an old railway track, it was still the greatest undertaking of this type in Poland during the last three decades.

Table 3: Currently dominating and future land-use forms [ha]; changes in the area of residential and service developments within an area of 660 m radius from the PMR stations in Gdańsk.

	Currently dominating land-use forms – residential,residential and service development	Future dominating land-use forms – residentialdevelopment with basic services, residential and service development
Gdańsk Brętowo	40,1	92,5
Gdańsk Jasień	14,4	55,1
Gdańsk Kiełpienek	16,6	49,6
Gdańsk Niedźwiednik	27,9	56,9
Gdańsk Strzyża	38,6	55,2
Gdańsk Matarnia	10,9	10,7
Gdańsk Port lotniczy	2,6	0,0
Gdańsk Rębiechowo	3,3	0,0

Source: own elaboration based on [20].

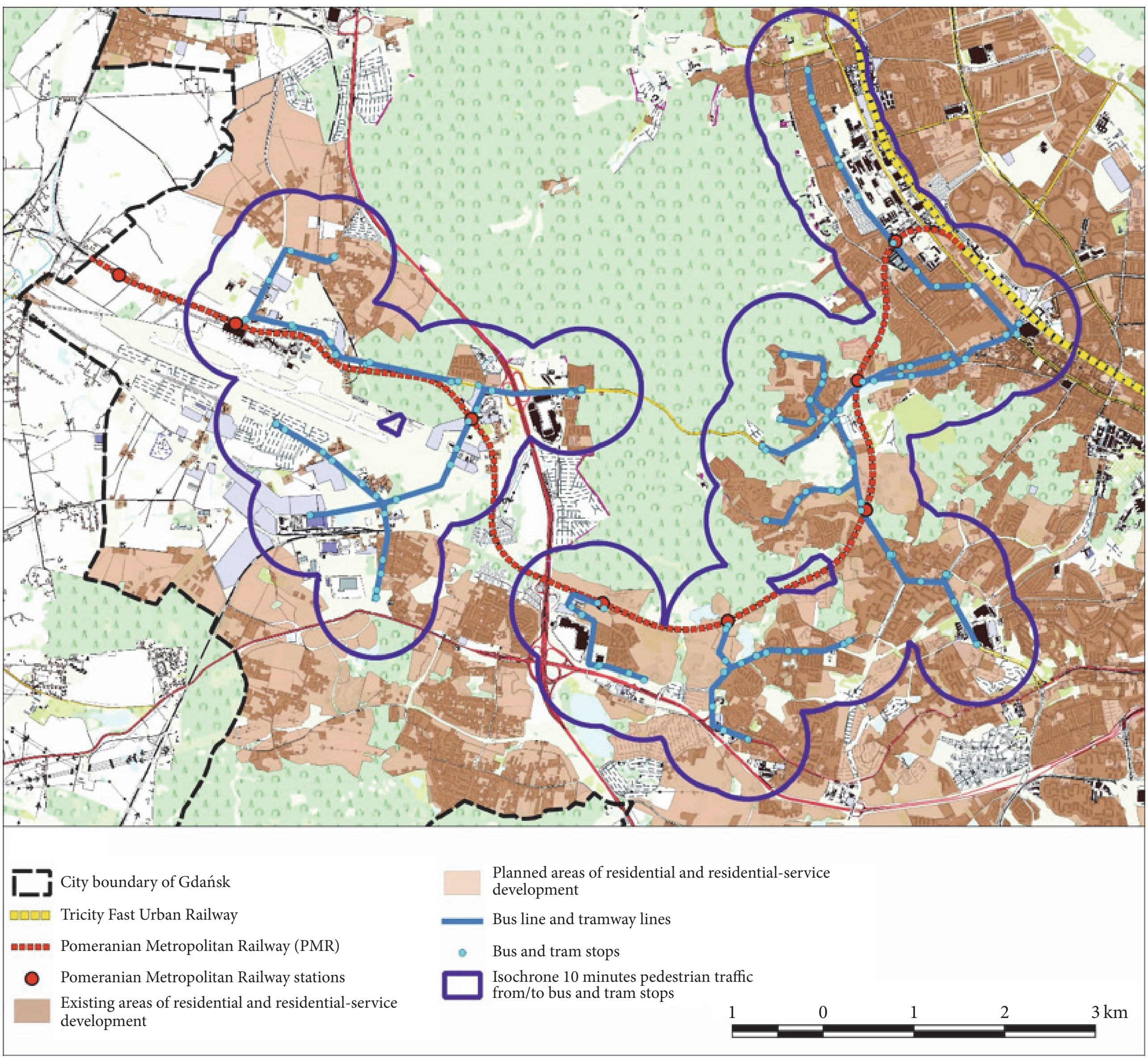

Figure 8: Directions and perspectives for development of areas around the PMR line (in the area of bus and tram transport services multimodal connections model).

The course of the line as well as the stations' location were largely affected by the landscape conditions and already existing infrastructure so there are not many potential passengers in the areas surrounding the PMR line. In 2016 in the zone of 10-minute walking distance to the new stations only 16,2 thousand people lived (population density was 15ppl/ha). In the zone of 20-minute walking distance a total number of residents was 62,8 thousand. However, the number of potential passengers could be higher as there are some public utilities located in close vicinity of the stations: the university campus (Gdańsk Strzyża), large shopping centre (Gdańsk Kiełpinek), industrial and service companies (Gdańsk Matarnia), and the airport and office centre (Gdańsk Port Lotniczy).

As the potential sources of passenger traffic are located far from the line, it was necessary to connect it by the means of public transportation system. Approximately 84 thousand people live within the zone of 10-minute walking accessibility to the nearest bus or tram stop allowing reaching the nearest PMR station in 5 minutes. However, the plan to connect the PMR line has not been fully implemented. In fact, only 27% of passengers were getting to the PMR station by bus or tram while 48% on foot. Thus, it can be stated that in order to increase the passenger traffic on this line, it is necessary to proceed with the integrating actions. The integration shall also comprise the tariff system. Lack of a common ticket tariff hampers introduction of the multimodal model.

Despite the above-mentioned unfavourable conditions, the number of passengers increased from 151,6 thousand in June 2016 to 190,0 thousand in March 2018. Wrzeszcz, Strzyża, and Jasień are the most popular stations among the passengers. Relatively large passenger traffic was also observed at Port Lotniczy and Kiełpinek stations. The least popular station is Niedźwiednik as it is located relatively near the central service district and well-connected by bus.

The PMR line in Gdańsk was planned to serve the airport as well as lower the traffic congestion on roads connecting the upper and lower terraces. In order to increase the number of people travelling by the PMR trains it is not enough to prepare a proper timetable and develop a network of multimodal linkages. Development of the residential function around the PMR stations is also of great importance. In order to do so, it was necessary to introduce some amendments to the general plan of spatial development. The document was adopted in April 2018 and according to its provisions it will be possible to develop an intense residential function in the closest vicinity of the PMR stations. There are three stations around which production, service, and logistic functions will be developed. When observing the ongoing changes on the housing market and some initial projects aimed at developing services and industry sectors around the PMR line, it may be stated that the plan to intensify the residential development in this area has sufficient prospect of success. Hence, the PMR line seems to have a significant impact on the process of urban form transformation.

Taking the main objective of the article into consideration, it has to be stated that launching the PMR has contributed to the changes in the functional and spatial structure of the city, yet to a limited extent. It is mainly because of a relatively short term of its functioning and limited accessibility to the train stops resulting from their peripheral location and the underdeveloped connecting lines system.

Most probably, some passengers do not use the line because the schedule does not match their needs; there is no integrated fee system and the passenger information system is not sufficient. Nonetheless, those issues have not been fully studied in this article so some further research on the passenger exchange and the passengers' motivation behind travelling by train shall be carried in the future.

A relatively short period of the new line operation makes it difficult to formulate any plausible conclusions on time variability. It is especially interesting to what extent the railway line contributes to reducing the car traffic. The analysis of data on the way in which passengers get to the PMR stations provided only superficial conclusions. Any changes introduced to the level of connectivity between the PMR line and the tram/bus system may help to identify the solutions which affect behaviour patterns of the passengers the most. Another interesting issue is the process of adopting new local development plans for areas surrounding the PMR stations as they will set the limits for their spatial development. Analysing strategies adopted by developers who are interested in investing in the areas surrounding the PMR line may also deliver interesting results.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Approach to the Weight Estimation in the Conceptual Design of Hybrid-Electric-Powered Unconventional Regional Aircraft

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The present work deals with the development of an innovative approach to the weight estimation in the conceptual design of a Hybrid-Electric-Powered (HEP) Blended Wing Body (BWB) commercial aircraft. In the last few decades, the improvement of the environmental impact of civil aviation has been the major concern of the aeronautical engineering community, in order to guarantee the sustainable development of the system in presence of a constantly growing market demand. The sustained effort in the improvement of the overall efficiency of conventional aircraft has produced a new generation of vehicles with an extremely low level of emissions and noise, capable of covering the community requirements in the short term. Unfortunately, the remarkable improvements achieved represent the asymptotic limit reachable through the incremental enhancement of existing concepts. Any further improvement to conform to the strict future environmental target will be possible only through the introduction of breakthrough concepts. The aeronautical engineering community is thus concentrating the research on unconventional airframes, innovative low-noise technologies, and alternative propulsion systems. The BWB is one of the most promising layouts in terms of noise emissions and chemical pollution. The further reduction of fuel consumption that can be achieved with gas/electric hybridisation of the power-plant is herein addressed in the context of multidisciplinary analyses. In particular, the payload and range limits are assessed in relation to the technological development of the electric components of the propulsion system. The present work explores the potentialities of an energy-based approach for the initial sizing of a HEP unconventional aircraft in the early conceptual phase of the design. A detailed parametric analysis has been carried out to emphasise how payload, range, and degree of hybridisation are strictly connected in terms of feasible mission requirements and related to the reasonable expectations of development of electric components suitable for aeronautical applications.

1. Introduction

For many decades, aeronautics and air transport have been an essential component of our global society: for all countries, this industry has a substantial impact on the global economic, social, and cultural development. The civil aviation system currently involves about 29 million employees worldwide through direct, indirect, and induced activities and ensures the transfer of passengers and goods from/to the most remote areas of the planet in a constantly decreasing time. As matter of fact, the aviation industry has constantly grown throughout the last century and is expected to further increase in the near future. The average annual rate of 4.4% in terms of transport capacity (revenue passenger kilometres, RPK) experienced over the period 1989-2009 [1] is foreseen to grow to more than 5% in the 2030 horizon [2]. This growth (see Figure 1) is mostly due to the progressive access to the civil aviation system of the emerging economies (such as Asia, Middle-East, Africa, and Latin America) with more than 6% RPK annual increment during the last decades [2, 3].

Although aviation currently accounts for only 2-3% (see Figure 2) of the 36 billion metric tons of CO_2 emissions of anthropic origin [4], these emissions are projected to grow in the foreseeable future as the air traffic increases: a 75% CO_2 increment was recorded between 1990 and 2012 and it is foreseen to grow 300% by 2050 unless preventive action is taken [5].

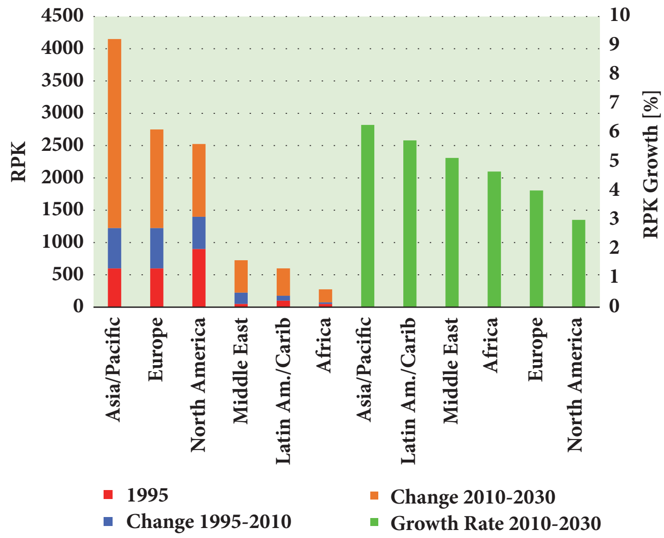


FIGURE 1: ICAO passenger traffic forecast by ICAO statistical region [9].

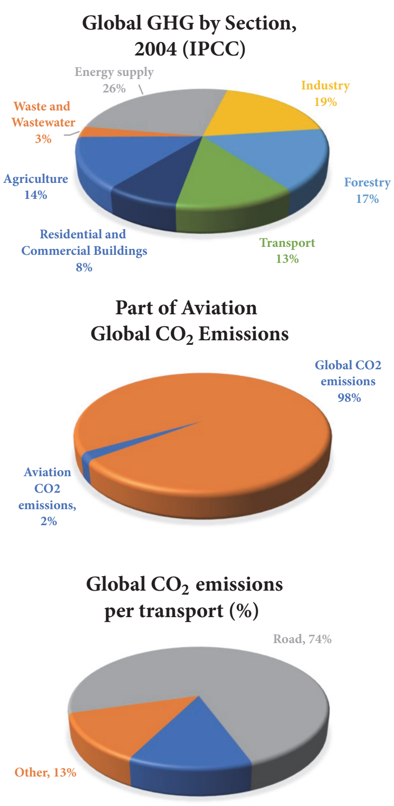


FIGURE 2: Aviation contribution to global CO_2 emissions [9].

However, carbon dioxide emissions are not the only contribution to the global warming of the aeronautical transportation system. Also the water vapour, cloud formation, ozone generation, methane reduction, particulates, carbon monoxide, unburnt hydrocarbons, soot, oxides of sulphur, and nitrogen oxides should be considered [6]. For sake of clarity, CO_2 and water vapour are grouped under the label Green–House–Gas (GHG) emissions responsible for the temperature of Earth's surface increase. As 90% of CO_2 emissions from global commercial aircraft are associated with vehicles carrying more than 100 passengers (twin-aisle and single-aisle aircraft), research should focus on developing innovative technologies to reduce emissions for large aircraft [7]. Most likely, these solutions will be then suitable for smaller aircraft as well.

With regard to Paris Climate Change Conference (COP21) in 2015, where it was established to keep the global temperature rise below 2°C compared to preindustrial levels [8], the contribution of air transport to global warming in the near future can no longer be ignored [6].

For these reasons, since the 90s, the international institutions involved have formulated quantitative goals for limiting Global GHG emissions establishing common targets to be fulfilled by the future aviation: CO_2 emissions per RPK reduction of 60% by 2035 and 75% by 2050 with regard to reference year 2000; NO_x emissions reduction of 84% by 2035 and 90% by 2050 with regard to year 2000.

The International Civil Aviation Organisation (ICAO) has developed since 2010 a number of measures which include technological standards, alternative fuels, operational and market-based measures aiming at promoting standards and regulations for aviation safety, security, efficiency, capacity, and environmental protection [9]. In order to concur with all the partner countries on the development of common trading schemes and policies for carbon neutral growth, ICAO established the Global Market-Based Measure (GMBM) in 2016 as an international agreement to tackle growth in carbon dioxide emissions of aviation industry from 2020 onwards [4, 6]. This action supports the 2035 global aviation industry as carbon neutral growth ambition and seems to be a promising mean to achieve the halving of CO_2 emissions by 2050 [12]. Among others, ICAO has established the Committee on Aviation and Environmental Protection (CAEP) to formulate new CO_2 Standard to be applied to aircraft of the next generation [4]. However, to satisfy these long term goals not only is effort from industries sufficient but also contribution from Government Institutions is necessary, on both Research and Development (R&D) and policy by means of, respectively, subsidises and new regulation for Air Traffic Management (ATM) [12].

Beside the environmental considerations presented, there are other motivations inducing an increasing interest in HEP aircraft. The airline companies are economically interested in reducing fuel burnt per flight due to the typical fluctuation of fuel price and its uncertain trend as fossil-fuel reserves will run short [7] (historical trend, provided by Federal Reserve Bank of St. Louis, is reported in Figure 3 for the period 01/2002–06/2018).

As it can be appreciated in Figure 4, IATA has reported in its Press-room Fact Sheets [13] that global commercial airline industry's fuel bill has been estimated to be 21% of total operating expenses in 2017 and it is foreseen to be around 24% in 2018.

As a short-term alternative to standard fuel, Sustainable Alternative Jet Fuels (SAJF) are strongly appealing the market [7, 14]. Potential alternatives that have been intensely studied include hydrogen, blending of ethanol and bio-diesel with conventional jet fuel, nuclear power, and compressed or liquefied natural gas. Ploetner et al. in [15] reported a comparison between possible scenarios for emissions reduction by means of new aircraft fleet and procedures in 2050. All studies considered in the paper have shown that available aircraft

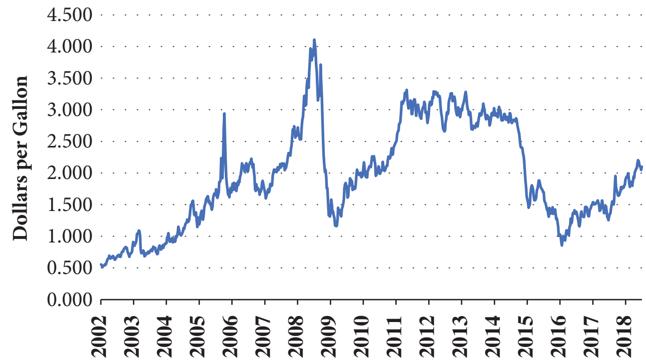


Figure 3: Kerosene-type jet fuel prices in US Gulf Coast [10].

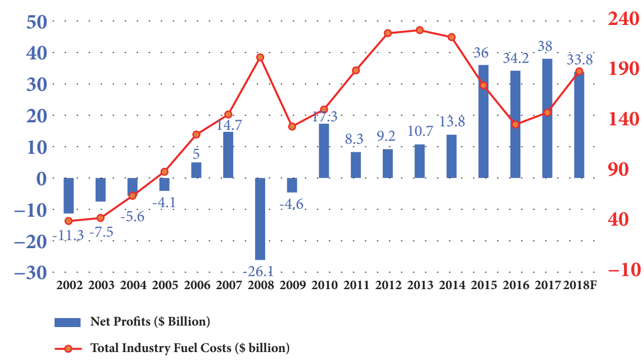


Figure 4: Industry fuel costs and net profits trends in aviation [11].

technology improvements are not sufficient to achieve the strict targets imposed by institutions for 2035 while air traffic grows. In a long-term scenario (2050), if novel configurations, radical technologies on aircraft level, alternative fuels, and ramp-up timelines in aircraft production are considered, GHG global emissions can be limited to 1.5 to 3.5 compared to 2005 baseline when air traffic growth is accounted.

Although dual energy sources and novel high-efficiency configurations are key aspects to accomplish the demanding request of emissions abatement, the current state of the art in specific power of each electric component and specific energy H_b of today's batteries (as well as low energy density ϱ_b) is still far from being effective for aeronautical applications. All the papers dealing with the issue of hybrid aircraft state that a key role is given to the efficiency of the elements that constitute the power-plant which makes electric hybridisation appealing for the reduction of GHG emissions in aviation. It is worth noting that, despite the high gravimetric energy of fuel H_f and the related energy density ϱ_f, the efficiency associated with conventional engine chain η_{ch}^{th} is rather low in comparison with electrical chain η_{ch}^{el}.

$$\text{Conv.}\begin{cases} \eta_{ch}^{th} \simeq 0.3 \\ H_f = 12.8\,kWh/kg \\ \varrho_f = 10.4\,kWh/l \end{cases}$$

$$\text{Elect.}\begin{cases}\eta_{ch}^{el} \simeq 0.85\\ H_b = 0.26\,kWh/kg\\ \varrho_b = 0.69\,kWh/l\end{cases} \quad (1)$$

Although the technological development of electric engines, controllers, generators, inverters, batteries, etc. is not advanced enough for aeronautical applications, it is necessary to identify which specific power, specific energy, and energy density are required to have an advantage in this field.

The reason why hybridisation is nowadays not yet feasible for commercial aircraft, while it can be considered as well established for ground vehicles, is the substantial weight and volumetric penalty of the electric components caused by the high level of energy and power required. Indeed, all alternative energy sources have a volumetric energy density much lower than kerosene and consequently weight, volume, and drag penalties must be taken into account to quantify the possible advantage of substituting traditional fuel [7]. Today, the fuel is stored in the wings of aircraft in order to accomplish few specific requirements: *(i)* it surrounds the centre of gravity to keep its position constant while fuel is burnt; *(ii)* its weight counter-balance the bending moment due to the lift force; *(iii)* it does not affect the volume for payload. Another important aspect is the weight reduction a conventional aircraft is subjected to during the mission as fuel is burnt. The amount of lost weight depends on the scheduled range and it is of course more significant for long-haul mission. This implies that the actual energy required for a fuel-powered aircraft would definitely be less than the energy required, for the same mission, of a battery–powered aircraft. As reported in [16] the minimum gravimetric energy of batteries required in aeronautics is about 500 kWh/kg and even so, the energy storage density will be 25 times lower than jet fuel corresponding to a high volume demand and additional weight. Moreover, safety is also an important aspect to be considered: all standards must be reviewed and changed in order to account for novel propulsion systems and energy storing.

Beside technical considerations, it is also mandatory to analyse whether these technologies would be costly effective for the demand market [17]. An envisioned starting point for electrification of aircraft is the application for Urban Air Taxis or regional segment [16]: until an acceptable repayment of investment for development and operating costs would not be demonstrated, airlines will not invest in such a product. For example, in case of regional segment, an aircraft generally flies 6–8 sectors per day so that the issue of high recharging speed and long life cycle batteries to maximise the number of occurring flights will be crucial for the investors. It can be concluded that, despite the promising emission reduction foreseen for alternative propulsion systems, there still exist significant limits with regard to market demand, technological development, and regulation and integration in existing infrastructures [17]. For these reasons it is crucial that further studies will be carried out in order to achieve a 360-degree view of the technological scenarios of the future.

The paper is organised as follows. Section 2 presents the main features of the BWB configuration, including the reference to a selection of works available in the literature on this specific concept. Section 3 deals with the fundamental definitions needed to address the performance analysis of a hybrid propulsion system. The conceptual approach developed in the present work is presented in Section 4, where the functional relationship between weight and hybridisation factor is obtained. Section 5 is dedicated to the analysis of the results obtained with the method presented: the region of feasible hybridisation in the space of the relevant parameters is determined through the Monte Carlo method with Latin Hypercube sampling for different mission profiles. Finally, Section 6 summarises the main outcomes of the work. Numerical simulations have been carried out using the MCRDO (Multidisciplinary Conceptual Robust Design Optimisation) framework FRIDA (Framework for Innovative Design in Aeronautics), briefly described in the Appendix.

2. Case Study: The Blended Wing Body Concept

The Blended Wing Body (BWB) is a tailless unconventional aircraft concept characterised by a *blended* functionality between the portions of the airframe dedicated to the payload allocation (the *fuselage*) and generation of lift (the *wing*). The BWB concept, with respect to tube–and–wings (TAW) layouts, turns out to have smaller aspect ratios and taper ratios. In addition, it allows to exploit a greater useful volume compared to that of the standard configurations and seems to be one of the most promising candidates for the future subsonic jetliners. It belongs to the flying-wing category and the ratio of the lifting surface to the wetted surface is increased with respect to conventional TAW layouts (see Figure 5) as well as a reduced wetted surface to volume ratio.

Several aerodynamic analyses and wind tunnel experiments have demonstrated that the lift to drag ratio is considerably improved (up to 20% with respect to classical configurations [18]), also due to the reduced interference drag. As a consequence, several advantages are foreseen, as the reduction of green-house gases emissions and the lower acoustic impact on the community. Furthermore, in several renowned studies, the benefits of BWB layout with respect to TAW configuration are given also in terms of fuel efficiency and Direct Operational Costs (DOC). Notwithstanding, it is worth noting that several issues, in both the design and the weight estimation, arise since the pressurisation of the noncircular cross-sections of the centre body is required. Moreover, due to the horizontal tail absence, the aspects concerning the longitudinal stability are crucial.

It is worth noting that, contrary to common belief, the revolutionary potential of BWB configuration over TAW layout has been grasped almost at the beginning of the aviation history [19, 20]. Several tailless biplane aircraft have been designed between 1911 and 1931, for example, the D–8 by John Dunne and the Hill's *Pterodactyl* series [21]. Furthermore, even the Northrop Corporation has been engaged in the development of flying-wings: it will suffice

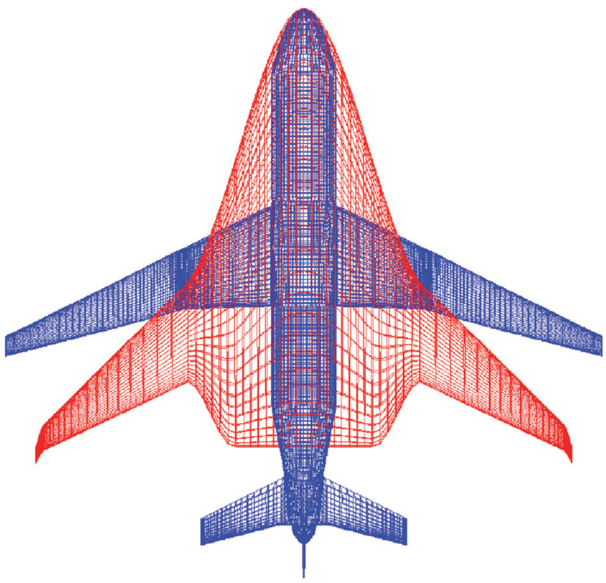


Figure 5: Comparison between tube-and-wings (TAW) and Blended Wing Body (BWB) layouts for a 110–pax class aircraft.

to consider the example of the N–1M, designed in 1940 and the N–9M [22]. Late in the World War II, the Horten Ho 229, designed in 1944 by Reimar and Walter Horten, goes down in history as the first flying-wing powered by jet engines. In 1947, another jet-powered prototype, the YB–49, has been developed by Northrop Corporation. Between 50s and 80s, two concurring facts have biased the research and the development of BWB aircraft: the huge growth of the commercial aviation industry, in which the reliable and well-assessed TAW configuration ensured the market stability, and the awareness of the flying-wing potential in military industry. These factors oriented the research mainly towards military applications. Notwithstanding, due to the success of the Grumman B2 Spirit, a strategic bomber designed by the Northrop Corporation, the interest in the BWB configuration for civil applications has been reawaken. Early studies of the BWB aircraft, as it is known today, have been conducted in the late 90s by the American aerospace company McDonnell Douglas (for a 800–pax subsonic transport aircraft with a mission of 7000 nm at a Mach number of 0.85 [23]), and after its merger with Boeing company an ever-increasing attention has been paid to the development of flying-wing concepts. One of the most renowned designs of a BWB is the X–48, conceived by Boeing in cooperation with the NASA Langley Research Center. Three versions of the prototype (X–48A, X–48B, and X–48C) have been developed between 2004 and 2012 [20]. A different BWB project was presented by Airbus Deutschland GmbH, with the aim of comparing a two-bridge configuration with the A380 (for a mission of 7650 nm with 700 passengers divided into three classes [24]).

On the European side, the 5th, 6th, and 7th Framework Programs (FP5, FP6, and FP7 programs) made possible the acquisition of knowledge and skills aimed at the analysis and development of BWB configuration for civil applications. The FP5 program includes the MOB (Multidisciplinary Optimisation of a Blended Wing Body [25]) and VELA (Very Efficient Large Aircraft [26]) projects: in the MOB project, a Computational Design Engine (CDE) for the BWB multidisciplinary design and optimisation was developed, whereas VELA analysed two BWB configurations (VELA 1 and VELA 2) used as baseline for the design of the VELA 3, a BWB aircraft powered by 4 engines mounted under the wing. During FP6, the NACRE project (New Aircraft Concept Research [27]) investigated the integration of concepts and technologies required for Novel Aircraft Concepts at aircraft component level (wing, fuselage, and engine integration) for novel aircraft. The project ACFA2020 (Active flight Control for Flexible Aircraft 2020 [28]), funded under FP7, produced the design of an innovative ultraefficient high-capacity BWB aircraft, following the ACARE guidelines. Finally, within Horizon 2020 program (H2020), the ARTEM project (Aircraft noise Reduction Technologies and related Environmental iMpact [29]) has been instituted in order to explore future aircraft configurations, as the BWB herein presented, in addition to other innovative concepts with integrated engines and distributed hybrid electric propulsion systems.

This brief (nonexhaustive) synthesis shows how not only the industry sector, but also academia always has had keen interest in the flying-wing configurations development. This fact reflects that both industries and research community are involved in the technological challenge of designing radically innovative aircraft to replace the existing, no-longer-sustainable fleet.

3. Hybrid Electric Propulsion: Main Definitions

When dealing with hybridisation of vehicles, beside choosing the power-plant that suits the application case, the designer must define whether the system is dominated by thermal or electric component [30]. For this purpose, over the years, several hybridisation parameters to quantify such domination were introduced by different authors. Some of these definitions are addressed here in chronological order.

Baumann et al. in [30] were the first to introduce the *degree of hybridisation* for hybrid electric vehicle (DOH_{HEV}) defined as the ratio of the maximum power output of implied energy conversion machines in the power train

$$DOH_{HEV} = 1 - \frac{\left|P_{max,EM} - P_{max,ICE}\right|}{P_{max,EM} + P_{max,ICE}} \tag{2}$$

where P_{max} is the nominal power output of the electric motor (subscript EM) and internal combustion engine (subscript ICE). The authors stated that $DOH_{CV} = 0$ is a conventional vehicle powered by ICE and $DOH_{HEV} = 1$ is a fully electric configuration. By means of this parameter, the designer determines the vehicle configuration (*i.e.*, parallel or series) and the control strategy.

In 2004, Lukic and Emadi [31] defined the *hybridisation factor* to conduct a study about optimal hybridisation level for parallel-hybrid electric cars

$$HF = \frac{P_{EM}}{P_{EM} + P_{ICE}} = \frac{P_{EM}}{P_{vehicle} = const.} \quad (3)$$

where P is the maximum power of electric machine (subscript EM) and internal combustion engine (subscript ICE) and $P_{vehicle}$ is the maximum total traction power to propel the vehicle. As for (2), HF can vary between 0, for conventional, and 1, for fully electric.

Other definitions were introduced by Buecherl et al. in [32], namely, the two *hybridisation factors*HF_1 and HF_2

$$HF_1 = \frac{P_{EM}}{P_{ICE}} \quad (4)$$

$$HF_2 = \frac{P_{EM}}{P_{EM} + P_{ICE}} \quad (5)$$

where P is meant as the available power for traction of the electromotive (subscript EM) and combustion (subscript ICE) engines. The authors aimed to find parameters to predict the hybrid vehicle performances, in terms of fuel consumption, additional cost and weight, reliability, and dimensions, all in once, by means of the aforementioned descriptors. Differently from the previous definitions, HF_1 can assume values from 0 up to infinity while HF_2 is bounded between 0 and 1. However, in [33] the authors assert that HF descriptors do not take into account the technical and economic characteristics of energy storage devices.

The descriptor HF_2 was successively adopted by Pornet et al. in [34] together with the *degree of electrification* (DE) previously discussed by Schmitz et al., in terms of exergy of the system, in [35].

$$DE = \frac{E_{Electric,inst.}}{E_{Total,inst.}} \quad (6)$$

This further synthesis function represents the ratio of the installed electric energy over the total installed energy to overcome the issue of accounting for the energy storage and conversion. The function DE is suitable for all kinds of energy sources (*e.g.*, jet-fuel, bio-fuel, battery, fuel-cell, and solar panel). In [34] a parallel-hybrid architecture is analysed. The restriction to this particular power train scheme comes from the definition of power at the drive shaft used in HF descriptor.

Lorenz et al. in [36] compared several hybrid power train concepts for all kinds of vehicles, from road vehicles to aircraft. For this purpose, they found a more general definition, the *degree of hybridisation* (DoH) for power

$$H_p = \frac{P_{em}}{P_{tot}} \quad (7)$$

where P is the maximum installed power of electric motor (subscript em) and of the sum of conventional engine and electric motor (subscript tot). Referring to the installed power, this definition is suitable for both serial and parallel systems. Moreover, because H_p does not account for energy storage, the authors suggest the use of an additional parameter for energy

$$H_E = \frac{E_{el}}{E_{tot}} \quad (8)$$

Inspired by the Ragone gravimetric diagram for batteries, which accounts for specific power and specific energy to classify energy storage devices, in [36] the authors depicted a two-dimensional space, by means of H_P and H_E parameters, to identify hybrid power systems.

In 2014 Isikveren et al. used the aforementioned definitions of H_p (ratio of maximum installed power) and H_e (ratio of energy source storage) in [37] to introduce a sizing methodology of dual-energy storage-propulsion-power system (DESPPS) of aircraft. Introducing new parameters for the operating time of each power chain during the flight mission, namely, the *activation ratio* (ϕ), and for the supplied power, the *supplied power ratio* (Φ), they connected the power and energy descriptors with a functional correlation.

$$\phi = \frac{\int_0^T \overline{\omega}_b dt}{\int_0^T (\overline{\omega}_a + \overline{\omega}_b)\, dt} \quad (9)$$

$$\Phi = \frac{P_{SUP,b}}{P_{SUP,tot}} \quad (10)$$

where ω is the power control parameter of electric (b) and conventional (a) supplied power in terms of duration of use within a designed mission. In the paper, they stated H_p to be a solely function of Φ whereas they stated H_E to be related to both Φ and ϕ. In [37] an example of a DoH trade study for DESPPS is reported in a diagrammatic representation, called *Onion Curves*, similarly as Lorenz et al. presented the Ragone diagram in [36]. In 2015, Pornet and Isikveren applied those figures of merit in [38] to quantify how hybridisation of aircraft can help reach the targets imposed by ACARE and EC.

A different approach was introduced by Marwa et al. in [39]. They define β as the total energy mass fraction and χ as the percent hybrid parameter, provided that the energy sources operate uncoupled. Depending on the selected power-plant different equations of the modified Breguet range formulation are given.

$$\chi = \frac{W_{battery}}{W_{battery} + W_{fuel}} = \frac{W_{battery}}{W_{energy}} \quad (11)$$

$$\beta = \frac{W_{energy}}{W_{energy} + W_{payload} + W_{EOW}} \quad (12)$$

By means of those parameters it is possible to write the derivatives of range and loiter equations with regard to χ variable so that a sensitivity analysis can be performed.

Recently, Voskuijl et al. in [40] analysed a parallel-hybrid configuration introducing two different approaches: constant power split ($S = cost$) and constant operating mode of gas turbine ($P_{em} = P_{shaft} - P_{gasturbine,const}$). The keyword of this work is to identify how and when to use the electric power. As matter of fact, beside the classic DoH parameters as defined in [37] and the *activation ratio* (ϕ), they introduced

$$S_i = \frac{P_{em,i}}{P_{shaft,i}} \tag{13}$$

In [40], the authors stated, when using a constant power split for all the mission phases, the supplied power ratio has approximately the same value as for the power split.

In the present study, a serial-hybrid configuration is considered as it better fits with a distributed electric fans propulsion. For this reason, the definitions of hybridisation parameters employed to investigate feasibility and benefit of dual-energy sources for aircraft are the ones referring to the electric and conventional installed powers reported in (7) and (8). Considering a constant power split for each mission segment, as suggested in [40], the DoH for power γ^H and for energy γ^E are linked to each other by means of the chain efficiencies so that they can be written as follows

$$\gamma^H = \frac{P_{el,inst}}{P_{tot,inst}} \tag{14}$$

$$\gamma^E = \frac{\gamma^H}{\gamma^H + (1-\gamma^H)\left(\eta_{ch}^{el}/\eta_{ch}^{th}\right)} \tag{15}$$

4. A Conceptual Approach to Aircraft Hybridisation

Aircraft design can be divided into three main phases, with an increasing level of detail. The first stage is the *conceptual design* and follows the *preliminary design* whereas the *detail design* precedes the manufacturing. It is widely felt that the conceptual phase is the most critical, as many requirements must be met (range, payload, speed specifications, etc.) together with regulatory compliance and environmental constraints. Due to this reason, in the last 20 years, optimisation techniques and conceptual design processes have made a strict dichotomy.

The conceptual stage first step is the estimation of the *take-off gross weight*, as long as the design mission does not include dropped payload or combat phases. The well-known take-off weight W_0 buildup method [41] starts from considering the aircraft weight at the initial instant of its mission as it follows

$$W_0 = W_c + W_p + W_f + W_e \tag{16}$$

W_c being the crew weight, W_p the payload weight, W_f the fuel weight, and W_e the aircraft empty weight. Note that W_c and W_p are known, as they are part of the mission requirements. On the contrary W_f and W_e, which are both functions of the total aircraft weight, must be estimated with an iterative process. Specifically, it is possible to handle (16), achieving the following form

$$W_0 = \frac{W_c + W_p}{1 - \left(\omega_e + \omega_f\right)} \tag{17}$$

where $\omega_e = W_e/W_0$ is the empty-weight fraction with W_e the aircraft empty weight, whereas $\omega_f = W_f/W_0$ is the total fuel fraction, W_f being the weight of the fuel burnt over the entire mission. The term ω_e can be computed using suitable fitting relations based on historical trends, and the regression coefficients are dependent on aircraft category. Instead ω_f, which must include the unusable fuel (about 6% of trapped fuel and reserve), can be evaluated as it follows

$$\omega_f = 1.06\left(1 - \prod_{i=1}^{N}\frac{W_i}{W_{i-1}}\right) \tag{18}$$

N being the number of mission phases, with W_{i-1} and W_i, respectively, the weight at the beginning and at the end of each phase. The fuel weight fractions related to warm-up and take-off, climb, and landing can be estimated using historical data, whereas one can calculate the cruise fuel weight fraction ω_f^C and loiter fuel weight fraction ω_f^E, by means of the Breguet equations as it follows

$$\omega_f^C = \exp\left(-\frac{R}{\left(\eta_p/BSFC\right)\big|_C (L/D)|_C}\right) \tag{19}$$

$$\omega_f^E = \exp\left(-\frac{E}{\left(\eta_p/BSFC\right)\big|_E \left(1/V_\infty\right)(L/D)\big|_E}\right) \tag{20}$$

where R is the mission range, E is the loiter endurance, η_p is the propeller efficiency, $BSFC$ is the brake specific fuel consumption, L/D is the aerodynamic efficiency, and V_∞ is the flight speed.

The described approach is quite inconsistent for hybrid electric aircraft, since both weight fractions ω_f and ω_e do not take into account electric components and, in particular, the weight of the battery pack which concurs to provide energy: it is therefore necessary to extend the standard weight estimation method by making some assumptions.

Let us consider the empty weight fraction ω_e: historical trends do not include hybrid electric aircraft, so it is not possible to include such category in the term ω_e in the regression used to solve (17). A valuable strategy could be the addition of the battery weight W_b within (16), so that additional masses can be taken into account during the iterative process that bring to the take-off weight calculation. As for the empty weight and the fuel weight, it is possible to define the battery weight fraction $\omega_b = W_b/W_0$. Given the above, (17) can be rewritten as it follows

$$W_0 = \frac{W_c + W_p}{1 - \left(\omega_e + \omega_f^H + \omega_b\right)} \tag{21}$$

Several techniques can be used in order to achieve a good prediction of ω_b, and the one used in this work is based on the total energy balance.

Let us focus now on the fuel weight fraction ω_f: by imposing the specific energies H_f and H_b and the conversion chain efficiencies η_{ch}^{th} and η_{ch}^{el}, for a given hybridisation ratio, there could exist a certain amount of required fuel in addition to the batteries to fulfil the mission. Of course, in case of fully electric configurations the fuel weight fraction equals zero, since the only electric energy is used. It is therefore possible to impose a functional relation between the fuel weight fractions and the hybridisation ratio in order to rewrite (18), such as the following

$$\begin{aligned} \omega_f^H &= 1.06 \left\{ 1 - \prod_{i=1}^{N} \left[\frac{W_i}{W_{i-1}} + \left(1 - \frac{W_i}{W_{i-1}} \right) \gamma_i^H \right] \right\} \\ &= 1.06 \left(1 - \prod_{i=1}^{N} \frac{W_i^H}{W_{i-1}^H} \right) \end{aligned} \tag{22}$$

$0 < \gamma_i^H < 1$ being a factor which takes into account the degree of hybridisation for the i-th mission phase. Recalling the Breguet equations, it is possible to interpret each W_i^H/W_{i-1}^H as the weight ratio of the current mission segment for an aircraft characterised by a lower fuel consumption, which does not necessarily mean that the aircraft consumes less fuel, due to the different power sources specific energies.

5. Results and Discussion

In this section, the preliminary weight estimation of a hybrid electric high-capacity regional BWB aircraft is presented. In order to assess the benefits introduced by hybridisation, a comparison between a conventional propulsion system and the novel hybrid electric configuration is addressed, for the same aircraft layout and mission. The presented BWB configuration is a first-attempt sketch where it was verified that the internal volume is sufficient for passengers (cabin), fuel, cargo, auxiliaries, and batteries. It was obtained without accounting any optimisation procedure, and, consequently, there still exists margin to improve its aerodynamic performances. The case study's mission requirements are summarised in Table 1, with the main relevant parameters.

Using the classical weight estimation procedure (already implemented in the framework FRIDA), the maximum takeoff gross weight has been estimated for the fixed mission profile in which the fuel and empty weight fractions are given as output. Following this approach, a Monte Carlo with Latin Hypercube Sampling (MC–LHS) varying the mission requirements, in terms of payload and range, can be carried out in order to estimate, for each coordinate of the range-payload plane, the required amount of fuel. In Figure 6 the obtained fuel masses are shown in a surface: the black curve identifies all those solutions for which the same amount of fuel is required, changing the payload and range parameters.

It is worth noting that the novel BWB, used for this work, has a centre-body layout such that the same payload is distributed in a shorter length (see Figure 5), without introducing space penalties, and the amount of fuel required to accomplish the mission is already lower due to the higher cruise aerodynamic efficiency with respect to a conventional configuration.

By means of the modified weight estimation algorithm, explained in the previous section, a feasibility study has been assessed within FRIDA, with regard to the technological

Table 1: Mission requirements and relevant parameters.

Parameter	Symbol	Unit	Value
Range	R	nmi	900
Payload	P	#	100
Crew	Cr	#	5
Cruise Mach	M	-	0.5
Altitude	h	ft	25000
Reference surface	S_{ref}	m^2	326.03
Total span	b	m	32.45
Total length	l	m	27.85
Aerodynamic efficiency (cruise)	$(L/D)_C$	-	19.0
Fuel consumption (cruise)	BSFC	g/(kWh)	211.0
Thermal chain efficiency (cruise)	η_{ch}^{th}	-	0.35
Propeller efficiency (cruise)	η_p	-	0.90
Fuel specific energy	H_f	kWh/kg	12.08

development of electric components. Focusing on the battery specific energy, a maximum DoH can be estimated for some expectations of H_b foreseen in the near future (*i.e.*, 2035, 2050 and over). Obviously the occurring limits depend on the mission requirements: the higher the range and payload, the higher the weight of batteries which consequently brings lower feasible DoH values. The obtained results are related to the mission requirements summarised in Table 1 and are shown in Figure 7.

These curves are parametrised through the technological level of batteries, where the lower value of H_b stands for today's specific energy of Li-ion batteries (250 Wh/kg). As it can be noted, for each curve an asymptotic limit occurs in correspondence with a certain γ^H which makes the battery weight such that (21), in the iterative procedure of weight estimation, returns an indefinite value. It is interesting to highlight that a minimum specific energy of battery, required to ensure a gain in terms of fuel burnt, is between about 500 Wh/kg and 750 Wh/kg for the presented case study.

In Figure 8 the feasible region of hybridisation has been traced performing MC–LHS analysis exploring the domain γ^H–H_b. The solutions represented by samples on the dark area are those for which about the same amount of fuel as for the conventional configuration is required, proving that hybridising the vehicle does not always provide an improvement. The area where the fuel burnt per mission starts decreasing is the right side of the oblique separation line, meaning that moving through the dark area the fuel amount remains constant. As a consequence, there will be only an increment in the gross weight without any reduction of fuel burnt. If the combination of γ^H and H_b returns a solution on the left side, it means that, despite hybridisation, the amount of fuel consumed is higher than its conventional propulsion counterpart. It is worth noting that, given today's H_b, whatever DoH is chosen, there is no convenience in introducing battery as additional energy sources for propulsion (see black square in the graph). Moreover, it is shown that, to have a fully electric configuration for this mission, batteries should have a specific energy of about 3.15 kWh/kg.

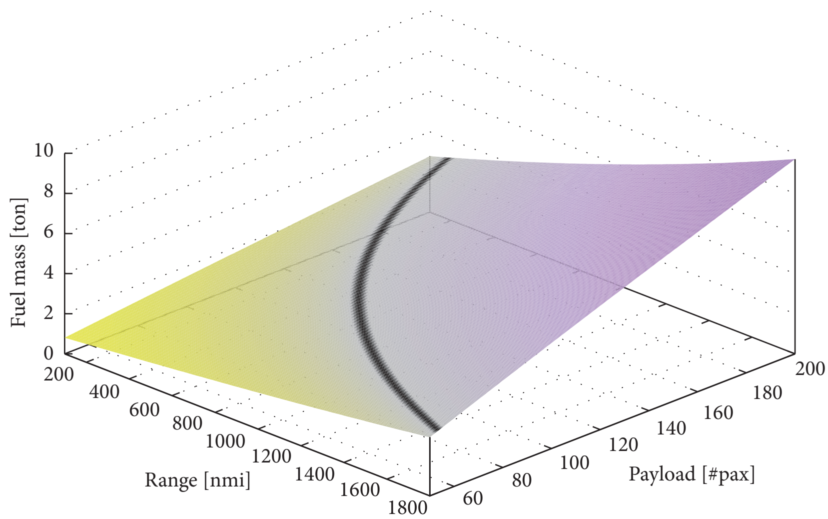
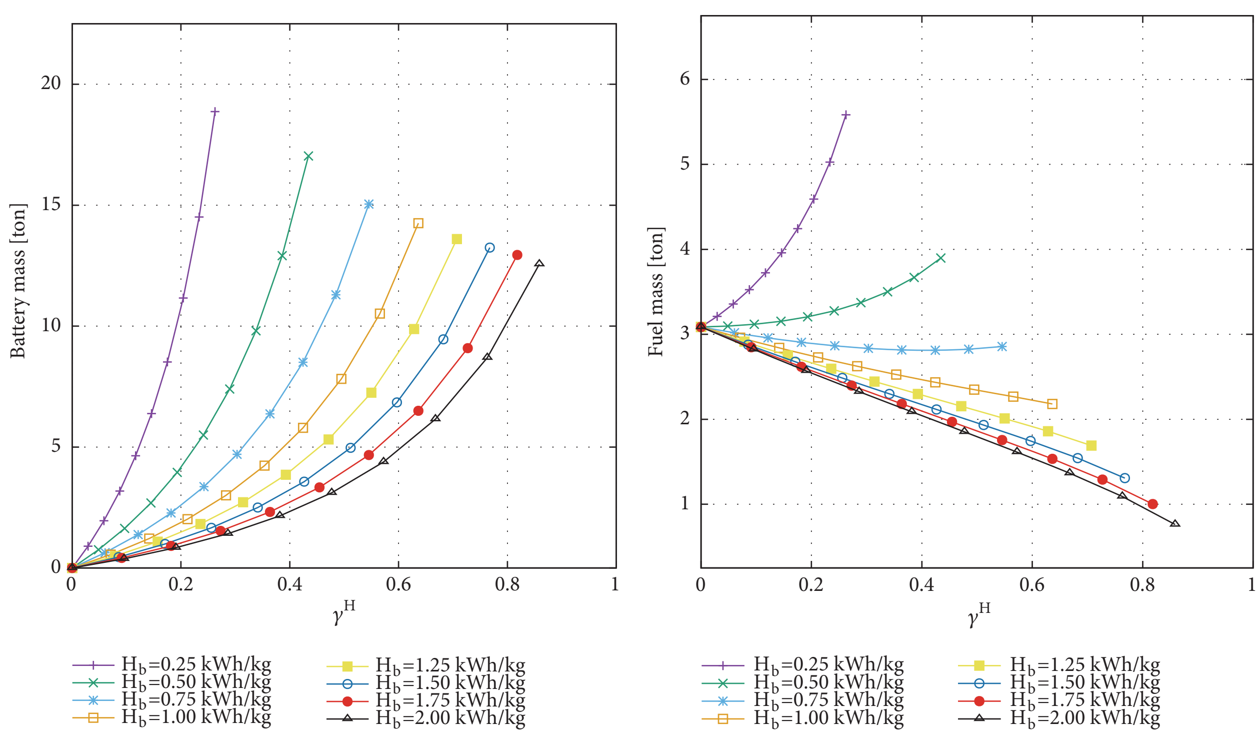


FIGURE 6: Maximum Take-Off Mass (MTOM) as a function of the design range and the number of passengers related to the regional BWB aircraft for $\gamma^H = 0$ (a): the black line indicates the design solutions characterised by the same amount of fuel burnt as the reference case.



(a) Battery

(b) Fuel

FIGURE 7: Battery-pack mass (a) and fuel mass (b) as functions of γ^H related to the regional BWB aircraft, with the battery specific energy as parameter.

In order to demonstrate the aforementioned states, other design spaces have been explored. In particular, the two extreme configurations, respectively, minimum and maximum range payload, are represented by the vertexes of the surface in Figure 6. Let us first analyse the result related to the minimum range and payload (50–pax and 100 nmi), depicted in Figure 9.

It is worth noting how the black demarcation line changes its slope becoming about vertical and translates towards the axis origin. Therefore, it is intuitive to catch that the smaller the gross weight, the lower the required gravimetric energy to have an advantage in the hybrid electric propulsion. Moreover, the technological level required to achieve a fully electric configuration also moves towards lower values of H_b. A different behaviour can be observed for the solution at maximum range payload (200–pax and 1800 nmi) in Figure 10.

The demarcation line changes its slope while moving towards right, *i.e.* higher values of H_b. In the analysed domain

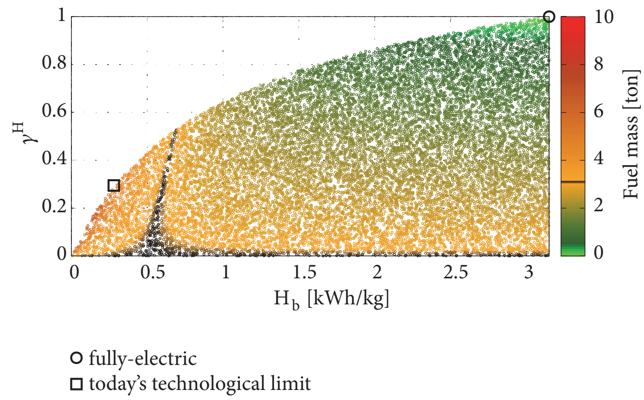


Figure 8: Parametric analysis of fuel mass consumption as function of degree of hybridisation and battery specific energy technology in comparison with iso-fuel solutions (black area) for the configuration characterised by mission requirements of a range of 100-pax and 900 nmi.

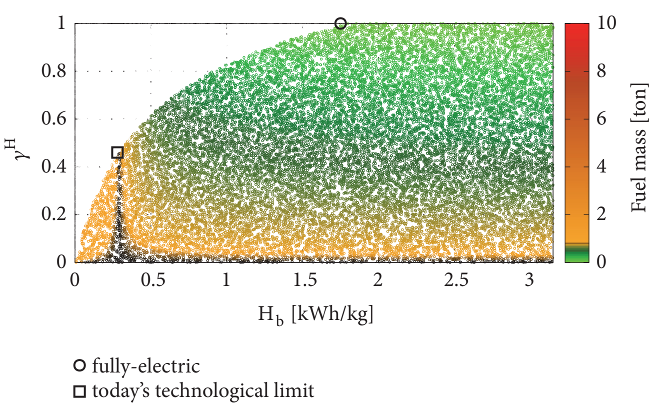


Figure 9: Parametric analysis of fuel mass consumption as function of degree of hybridisation and battery specific energy technology in comparison with iso-fuel solutions (black area) for the configuration characterised by mission requirements of 50-pax and a range of 100 nmi.

Table 2: Hybrid electric chain relevant parameters.

Parameter	Symbol	Unit	Value
Battery specific energy	H_b	kWh/kg	1
State of charge	SoC	-	0.20
Electric chain efficiency	η_{ch}^{el}	-	0.85
Electric motor efficiency	η_{em}	-	0.98
Generator efficiency	η_g	-	0.95

there does not exist any point in the design space for having a fully electric configuration. In addition, the interesting case of $H_b \approx 1$ kWh/kg provides a gain or a loss, in terms of required fuel, depending on the selected value of γ^H.

Finally, from the simulations performed above, it can be concluded that, for the mission in Table 1, hybrid electric propulsion with battery and fuel as dual-energy sources is foreseen for 2050 when a specific energy of 1 kWh/kg is assumed to be a realist prevision. Given this parameter and others reported in Table 2, the modified weight estimation algorithm presented in Section 4 has been used to carry out the initial sizing of a hybrid electric propelled BWB.

For the sake of clarity, four different cases of DoH have been analysed:

(i) the conventional configuration with $\gamma^H = 0$;

(ii) the case of $\gamma^H = 0.65$, corresponding to the maximum achievable DoH for this mission;

(iii) the case of equal distribution between fuel and battery weight at take-off, $\gamma^H = 0.26$;

(iv) the solution relative to the minimum utopia point distance for a biobjective optimisation problem aimed at minimising both the fuel and the battery weights, varying H_b and γ^H: the optimisation problem has been solved using FRIDA by means of MODPSO algorithm and returned the solution $\gamma^H = 0.38$.

In Figure 11, a comparison of weight percentages with regard to the resulting MTOM of battery, fuel, payload and crew, and empty weight is shown.

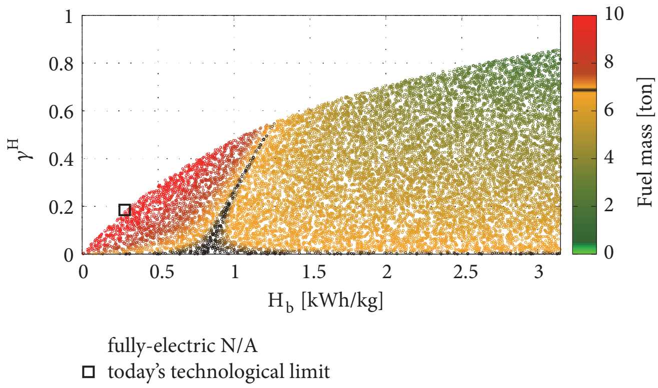
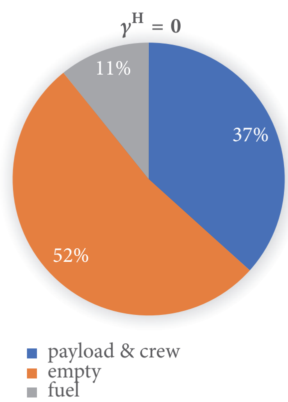
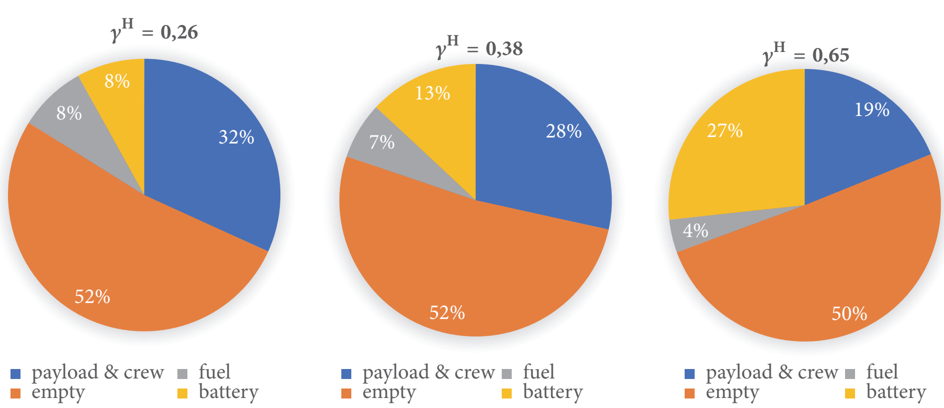


FIGURE 10: Parametric analysis of fuel mass consumption as function of degree of hybridisation and battery specific energy technology in comparison with iso-fuel solutions (black area) for the configuration characterised by mission requirements of 200-pax and a range of 1800 nmi.



(a)



(b) (c) (d)

FIGURE 11: Regional high-capacity BWB aircraft MTOM breakdown for $\gamma^{H} = 0$ (a), $\gamma^{H} = 0.26$ (b), $\gamma^{H} = 0.38$ (c), and $\gamma^{H} = 0.65$ (d).

As it can be deduced from Figure 11, the empty weight fraction ω_e is about constant as γ^{H} increases. This is due to the overall weight increment because of the presence of the battery pack, which requires a more resistant, and consequently heavier, structure. Moreover, the masses breakdown highlights the gain in terms of fuel burnt while the hybridisation factor increases.

6. Conclusions

This paper explores the hybrid electric BWB aircraft configuration initial sizing methodology. Since the current technology is approaching a saturation point, innovative layouts must be defined. Accounting for the challenging targets imposed by authorities, the feasibility of introducing alternative energy source in aviation has become common together with the research of novel airframe design solutions. It is intuitive to understand that such dichotomy turns out to be an important technology breakthrough. Exploring the classical weight estimation methodologies to extend it for unconventional propulsion system, foreseen in the near future, is the essence of this work. After a synthesis of the main definition introduced over the last decades to account dual-energy sources for vehicle's propulsion, the modified version of the weight estimation procedure for the aircraft initial sizing has been outlined. Through the modified algorithm, several MC–LHS analyses have been performed with the aim of clarifying the functional relations between mission requirements and technological development. Results have confirmed how feasibility and technology are strictly connected to each other so that not only the achievable DoH but also the effective gain is left to the future technological development.

Appendix

The MCRDO Framework FRIDA

The Multidisciplinary Conceptual Robust Design Optimisation (MCRDO) framework FRIDA (Framework for Innovative Design in Aeronautics) has been used for the analyses presented in this work. FRIDA can deeply describe the aircraft from a multidisciplinary point of view, so that it turns out to be suitable for all those applications that require the aircraft configuration definition, the environmental impact estimation (taking into account both the acoustical and chemical emissions) combined with financial metrics. It is worth noting that, FRIDA being developed to assess the conceptual design of both conventional and innovative aircraft (for which the designer cannot rely on past experience or literature data), the algorithms used for the aircraft analysis are, whenever possible, prime-principle based.

The aerodynamic analysis makes use of an integral formulation based on a quasi-potential flow [42]. The formulation is coupled with a boundary-layer integral model to take into account the effects of viscosity providing an adequate estimation of the viscous drag, which is essential for the study of flight mechanics and performance analysis.

$$\begin{aligned}\varphi(\mathbf{x},t) &= \int_{S_B}\left(G\chi - \varphi\frac{\partial G}{\partial n}\right)S(\mathbf{y}) \\ &\quad - \int_{S_w}\left[\Delta\varphi_{TE}\right]^{\tau}\frac{\partial G}{\partial n}dS(\mathbf{y})\end{aligned} \tag{A.1}$$

The numerical solution of (A.1) is provided by a zeroth-order Boundary Element Method (BEM). FRIDA can also simulate entire missions, and suitable corrections are used to take into account the aerodynamic effects of high-lift devices (flaps and slats), air-brakes, and landing gears [41]: the decision lies in the goal of reducing the computational costs, since an aerodynamic analysis at each sample of the trajectory would be too time-consuming.

The flight mechanics are solved in order to guarantee the static longitudinal stability, fundamental requirement for each flight condition, by imposing that the derivative of the pitching moment with respect to the centre of gravity is less than zero.

$$\frac{dc_m}{d\alpha} < 0 \tag{A.2}$$

The structural weight evaluation is addressed starting from the knowledge of the characteristic dimensions of the wing and tail elements (spars, stringers, ribs, and coverings) and the fuselage geometric sketch: subsequently the weights of engines, landing gear, and fixed equipment are added. An accurate analysis of masses distribution at each sample of the trajectory (including payload, crew, fuel, and operational items) allows the estimation of the actual position of the centre of gravity.

A 6–DOF torsional-bending beam equivalent model of the wing is assessed within FRIDA, and the nodal generalised forces due to the aerodynamic loads are computed. The modes of vibration and the natural frequencies of the beam representing the wing are also calculated. The solution of the structural problem is determined using a modal approach considering constant boundary conditions in the joint sections of wings and tail surfaces with the fuselage or the centre body in the BWB configuration. The approximate modes of vibration are calculated with a Finite Element Method (FEM) model of the wing, using the following representation for the displacements

$$\mathbf{u}(\mathbf{x},t) = \sum_{m=1}^{M} q_m(t)\,\Phi_m(\mathbf{x}) \tag{A.3}$$

The solution of (A.3) allows the estimation of the diagonal matrix Ω of the natural frequencies of the beam representing the wing. The module also evaluates the nodal generalised forces due to the aerodynamic loads acting on the wing, thus the direct and shear stresses distributions: this allows computing both the normal and the shear stress at the wing root location.

The flutter and divergence speeds estimation is also performed in FRIDA. To carry out an efficient aeroelastic analysis, a reduced order model (ROM) based on a finite-state approximation is employed for the evaluation of the matrix collecting the aerodynamic forces [43].

The analysis of entire mission requires the knowledge of the engine operating points at each sample of the trajectory. Since the complete engine thermofluidynamical analysis would be too burdensome, a semiempirical turbofan model, based on both prime-principle and available experimental data, is implemented within FRIDA. For a given flight condition, knowing the engine features, such a model provides the percentage of throttle as a function of the flight mechanics variables (altitude, drag force, actual aircraft weight, acceleration of the aircraft, etc.) and the propulsion system characteristics (number of engines, engine pitch, bypass ratio, maximum thrust per engine at sea level, etc.). For each operating point, the jets velocity is calculated through the momentum equation and their temperatures are estimated with the energy balance. Thereafter the amount of fuel consumed is also estimated, in order to update the current aircraft weight.

The aeroacoustic models within FRIDA allow the estimation of the airframe noise [44, 45], the fan/compressor noise [46] and the buzz–saw noise [47] as a function of the distance from the observers, the directivity (polar and azimuthal) angles, and the actual aircraft configuration, in terms of wet surfaces and engine operating point. The jet noise is evaluated by means of polynomial regressions of experimental data. For the calculation of the 1/3 octave band Sound Pressure Level (SPL), the algorithms also take into account the Doppler effect, the atmospheric absorption [48], and the ground reflection. Through a proper postprocessing, the Sound Exposure Level (SEL) and the Effective Perceived Noise Level (EPNL) are also estimated. Moreover FRIDA includes an innovative sound quality assessment method [49–52], developed during progression of EC-funded SEFA (Sound Engineering For Aircraft, FP6, 2004–2007) and COSMA (Community Noise Solutions to Minimise aircraft noise Annoyance, FP7, 2009–2012) projects. In addition, suitable metamodels for taking into account the noise shielding effects for BWB configuration have been recently implemented [53, 54].

FRIDA also includes a financial module which allows the estimation of financial implications from an airline company perspective [55–57]. Positive cash flows (related to revenues) and negative cash flows (fuel and maintenance costs, and social costs related to noise pollution) are estimated and actualised in order to estimate the Net Present Value *NPV* of the airliner.

The single-objective minimisation algorithms implemented in FRIDA are the sparse–SQP, Sequential Quadratic Programming [58, 59], and the `FORTRAN GA`, a Genetic Algorithm developed by [60]. The multiobjective minimization algorithms are two gradient-free methods. The first is the `NSGA-II`, Non-dominated Sorting Genetic Algorithm, described by [61]. The second one, recently implemented, is a Particle Swarm Optimisation (PSO) algorithm, introduced by [62]: the PSO implementation peculiarity lies in the deterministic distribution (MODPSO) of the particles and has been developed by the *Resistance & Optimisation Team* [63, 64] of the CNR–INSEAN (a detailed analysis of the impact on the solution due to the initial particles position can be found in literature [63], as well as an initial comparison between the `NSGA-II` and the MODPSO efficiencies [52]).

Data Availability

The data used to support the findings of this study may be released upon application to the coordinator of the ARTEM project (H2020, grant agreement No. 769350), who can be contacted through the third author at umberto.iemma@uniroma3.it.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Aspects of Improvement in Exploitation Process of Passenger Means of Transport

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Effective exploitation of means of transport in transport companies is one of the most important ways of achieving competitive advantage. Mentioned problem is particularly important in the market of passenger transport services in large agglomerations, because it has a social aspect in addition to the economic dimension. In addition, most often the studies concern single objects of exploitation, while the subject of research are groups of objects of passenger transport means. The main objective of the study is to analyze and evaluate the system of exploitation of passenger transport means and to propose solutions for its improvement. On the basis of the theory of exploitation systems, quantitative utilitarian models have been built, which have been verified by applications using data obtained from Municipal Communication Company (MPK) in Wroclaw. Originality and innovation in the recognition of the research problem consist in applying to the analysis and evaluation of the Ishikawa diagram exploitation system, Pareto-Lorenzo analysis, and FMEA (Failure Mode and Effects Analysis) methods. On the other hand, a QFD (Quality Function Deployment) diagram was used to build a model of improvement of the exploitation system, with the use of which the target values of parameters for the operation of MPK passenger transport in Wroclaw were determined. The applied methods, techniques, and research tools are rarely used in the field of testing of vehicle operation systems. The work has a very practical character and built models can be used in other urban agglomerations in order to improve the operation of passenger transport means.

1. Introduction

Currently, one of the most important problems of city management is the issue of communication and development of urban transport systems [1–4]. This is mainly caused by a large number of vehicles on the road, low capacity of selected transport routes, and relatively weak condition of the linear transport infrastructure [5, 6]. In urban areas with a significant density of road infrastructure, solving transport problems by expanding the infrastructure is not very effective, because any bandwidth reserve obtained in this way is immediately used [7–9]. Among the effective methods of improving the efficiency and quality of the transport system, the use of advanced technological and organizational solutions is mentioned [10–13].

Efficient use of means of transport in any type of company is one of the major ways to achieve competitive advantage [14–17]. This problem is particularly important in the area of passenger transport market in large agglomerations, because except its social aspect it also has the economic dimension. In addition, most of the studies concern individual facilities, while the subject of research are groups of objects of means of passenger transport.

The issue of evaluating and improving the exploitation system of means of passenger transport is an extremely important issue from a practical and a theoretical point of view [15, 18, 19].

The main objective of the study is to analyze and evaluate the operation of the system of passenger transport and to propose solutions to improve it.

In the process of development of analysis and evaluation of the operating system, Ishikawa diagram, Pareto-Lorenz analysis, and FMEA (Failure Mode and Effects Analysis) [20], among others, have been used, while the QFD (Quality Function Deployment Diagram) was used to build a model for the improvement of the exploitation system, which determined

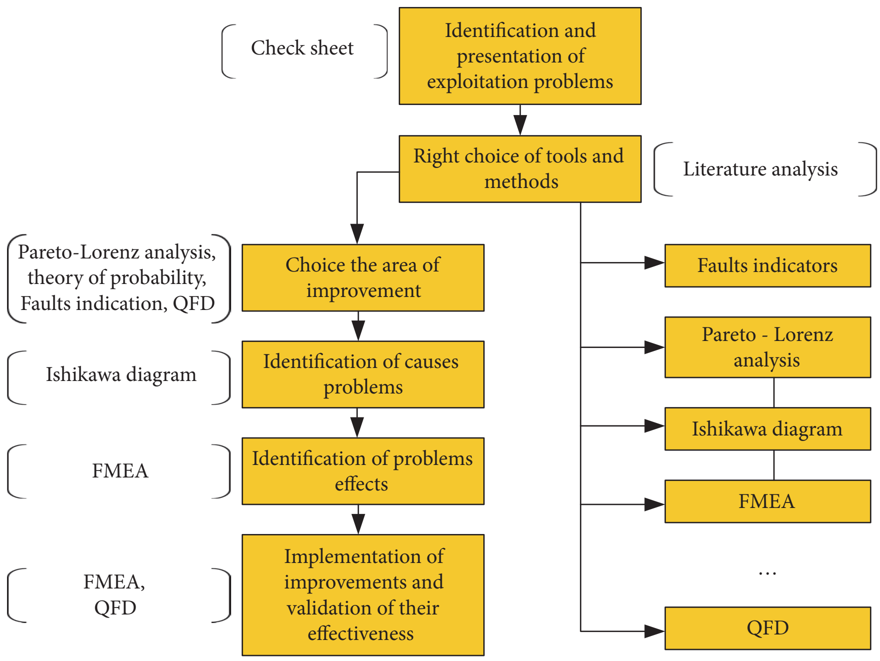


Figure 1: Improvement model of the exploitation process of means of passenger transport, on the example of urban buses.

the target values of the exploitation parameters of MPK passenger transport in Wroclaw [9, 21, 22]. The methods, techniques, and research tools used are rarely applied in the field of vehicle operating systems.

2. Modelling the Improvement of Exploitation Process of Means of Passenger Transport

2.1. Assumptions to Build a Model for Improving the Exploitation Process. Proper exploitation of buses contributes to the fulfilment of a certain level of quality of transport services. Operational technical parameters are used to assess these services [23]. With the development of cities and the increasing number of people in agglomerations, transport companies have to constantly search for optimal solutions. One of them is, among others, improvement of the vehicle exploitation process, which will ensure their reliability at a high level [21, 24, 25].

The article presents the model of improvement of the exploitation process and its verification on the example of urban public transport company in Wroclaw. This verification will be based on the analysis of bus damage from the year 2014. The study was carried out on the basis of selected systems failures occurring on buses, such as the braking system, electrical system, bodywork, transmission system, suspension system, steering system, engine with attachments, and chassis [22, 26, 27].

In Poland there are 12 agglomerations treated as metropolises belonging to the Union of Polish Metropolis: Bialystok, Bydgoszcz, Gdansk, Katowice, Cracow, Lublin, Lodz, Poznan, Rzeszow, Szczecin, Warsaw, and Wroclaw. Giving the city the character of a metropolis is to sanction the specifics of highly urbanized areas, stimulating the comprehensive economic development of the whole country. There are 17 million people living in metropolitan areas, over 40% of Poles. These cities produce 42% of Poland's GDP.

Accordingly, in the workplace of the place where the analysis of urban bus damage was carried out, the City Transport Company was selected, Wroclaw. The company has a large number of vehicles, due to its high density of population and a strong urban character of the city, which has made the most reliable test results possible, hence the choice.

Infrastructure of the Municipal Communication Company in Wroclaw (MPK Wroclaw) consists of 65 bus lines: 52 daily lines and 13 night lines. Fleet of MPK Wroclaw consists of over 300 buses, including 69 city bus subcontractors-Michalczewski Sp. z o. o. Out of all the bus operators that are stationed in city car barns, an analysis was performed on the damage of 110 selected buses.

2.2. Model of Improvement in the Process of Exploitation of Passenger Means of Transport. In city transport, the key element of management is control and the provision of the highest possible quality of service. This requires constant monitoring of the current state of affairs and processes to ensure their efficiency. Figure 1 shows improvement model of the exploitation process in means of passenger transport on the example of the Urban transport company (MPK Wroclaw).

3. Application of the Model for Analysis and Evaluation of the Passenger Transportation System

The first step in the improvement model is the identification and presentation problems of exploitation of the vehicle

Table 1: Damages and exploitation data of city bus operator MPK Wroclaw from 2014 within 1 year.

Name of damaged bus system	Model of the bus				
	Mercedes-Benz O530 K Citaro	Mercedes-Benz O530 Citaro	Mercedes-Benz O530 G Citaro	Mercedes-Benz O530 G Citaro 2	Jelcz 120MM
Braking system	11	56	48	8	217
Electrical system	19	89	71	10	167
Bodywork	2	52	32	1	184
Engine with attachments	0	16	14	2	134
Suspension system	5	37	29	1	15
Steering system	5	18	15	3	13
Transmission system	12	60	46	8	39
Chassis	0	20	15	2	31
Number of bus failures-LU	54	348	270	35	800
Average age [years]	3	5,7	5,7	3	18,7
Total bus mileage-P [km]	65,818	4,496,745	2,709,404	54,824	395,631
Number of buses (total)	1	58	42	1	8

group under study. It was done with a check sheet for damage to individual systems of different models of city buses. In addition, the average age and mileage of vehicles are reported. The data is shown in the Table 1.

The study was conducted on 110 city buses divided into 5 types:

(i) Mercedes-Benz O530 Citaro K-Class MAXI
(ii) Mercedes-Benz Citaro O530-Class
(iii) Mercedes-Benz Citaro O530 G-Class MEGA
(iv) Mercedes-Benz Citaro O530 G 2-MEGA
(v) Jelcz 120MM-Class MAXI

The second step for improving the operation process is to choose the proper methods and tools. Based on the analysis of literature and the results of the years of research in the field of improvement of operation, test sheet, analysis of Pareto-Lorenz, indicators of damage, Ishikawa diagram, FMEA, and QFD were chosen.

The third step of the improvement model is the choice of areas of improvement, which is to determine what damage should be seen about first. For this purpose, the Pareto-Lorenz graph was used. On the left side the total number of defects is found; on the right, the percentage of defects is found.

Analysis of the graph in Figure 2 shows that 80% of all the damage is caused by 4 systems: the electrical system, brake system, bodywork, and engine with attachments. This means that they need to be addressed first. For verification of this method of work, a fault indicator of individual systems of the type was also used. The damage analysis was based on the selected operational data of the Wroclaw City Bus Operator-MPK Wroclaw. An assessment of the number of damage to a certain type of system per thousand kilometers over one year of usage was made by using a W index that was determined from the relationship:

$$W = \frac{LU'}{P} \times 10^3 \qquad (1)$$

where LU' is number of defects of each team within 1 year, P is total mileage of buses of a given type within 1 year.

The analysis mentioned in Figure 3 takes into account vehicle mileage and determines the failure rate for each of the systems considered, for each 1000 km traveled. It can be said that Jelcz 120MM has the highest damage index in 5 out of 8 systems: bodywork, electric system, brake system, chassis, and transmission system. The Mercedes-Benz O530 K Citaro has the lowest damage rating in 3 of the 8: suspension system, steering system, and engine with attachments (Figure 3).

After defining areas for further research, one must move on to the next, fourth stage of the model, identification of causes and propose solutions to problems. To that end, examples of potential causes are presented, in the form of Ishikawa diagrams (Figure 4), and there are proposed solutions in the form of Table 2 for each of the previously specified systems, for

(i) braking system, weak braking,
(ii) electrical system, problems with starting the engine,
(iii) bodywork, corrosion of the bodywork,
(iv) engine with attachments, weak air conditioning.

The Isikawa diagram allows identification of possible causes of damage. Figure 4 shows an exemplary Ishkava diagram for the engine system with attachments divided into 6 main causes of damage: materials, machines, personnel, measurements, methods, and environment.

Table 2 presents examples of solutions of the described problems for all systems. The table has been divided into three

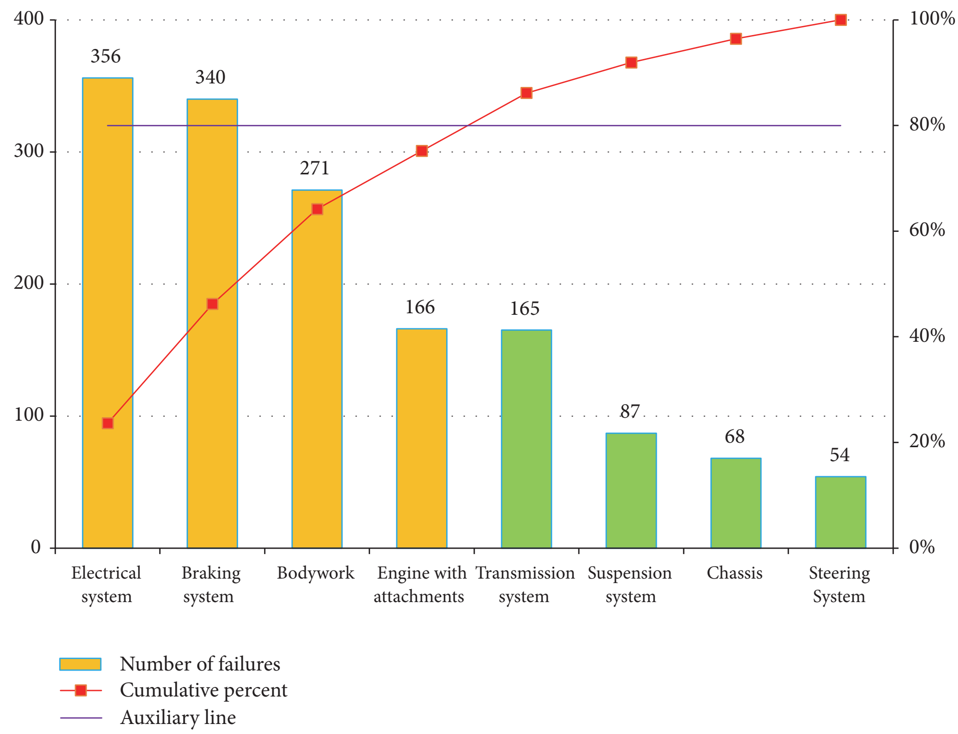


Figure 2: Pareto-Lorenz diagram of damage to individual bus systems based on the control sheet.

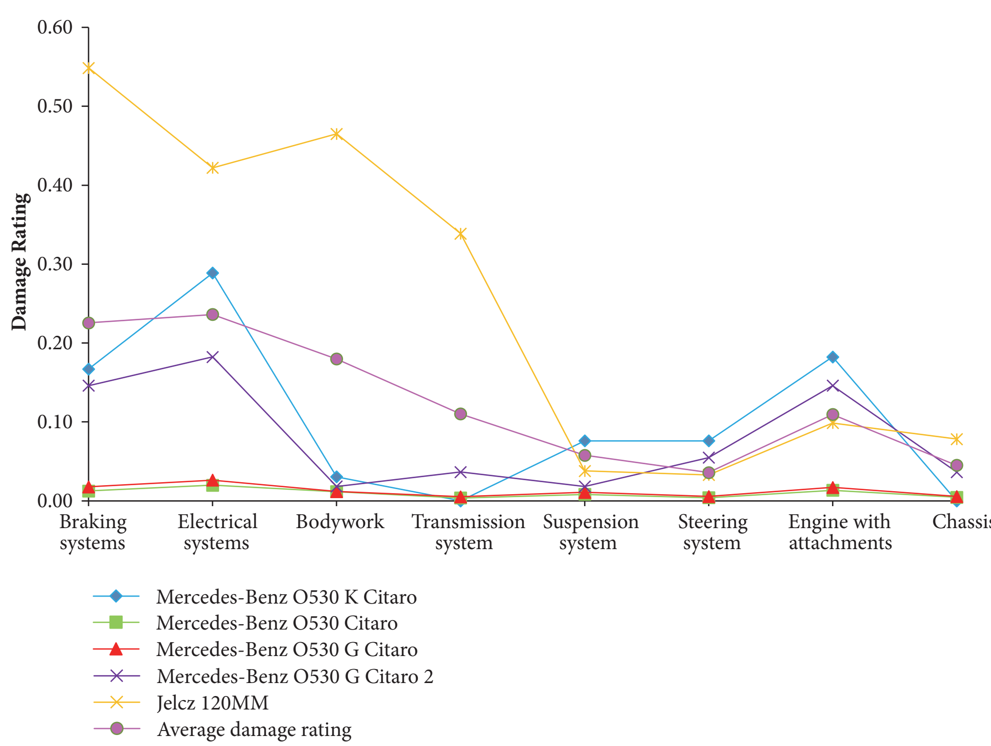


Figure 3: Damage indicators of individual buses of MPK operator Wroclaw.

columns: type of problem, its cause, and suggested solution. Considering the first system, the biggest problem and the cause of corrosion of the body are weak storage and improper maintenance. Therefore, actions are necessary to improve the storage and maintenance of buses by providing vehicles with heated garages (in winter), washing them frequently, and protecting them with protection measures. Problems with the engine system with attachments include inefficient air

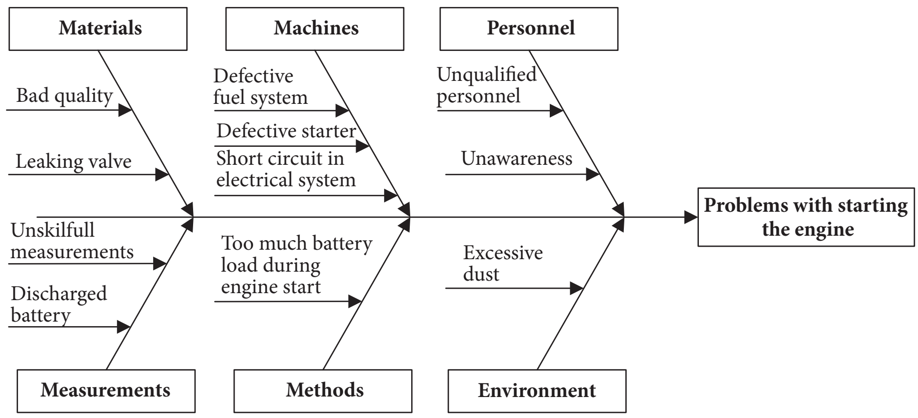


Figure 4: Ishikawa diagram for the electrical system.

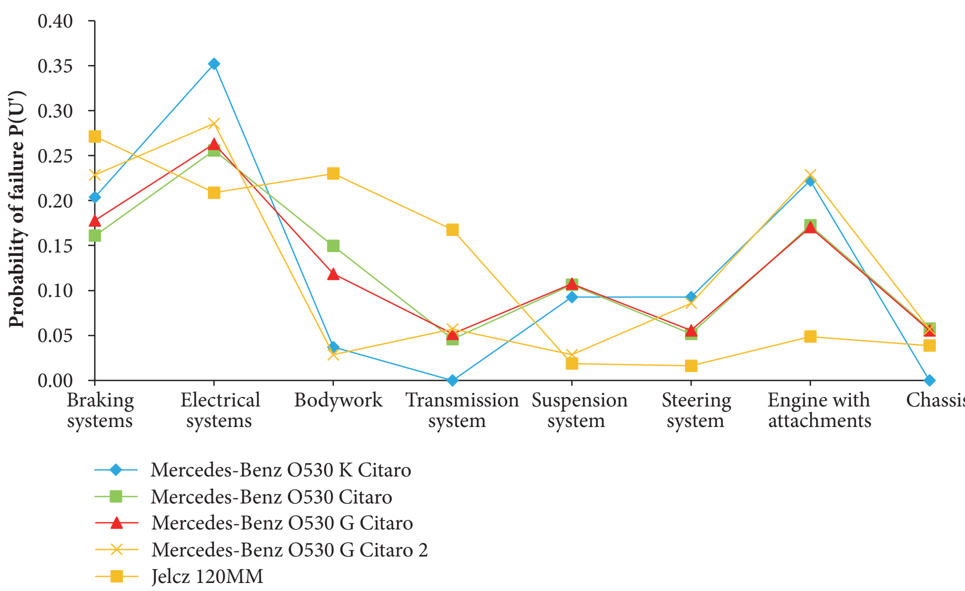


Figure 5: Values of the probability of failure for each of the bus systems in city buses.

conditioning. The main reasons for this issue can include primarily improper handling and use of the system. The proposed changes include starting the air conditioning system with the windows closed (securing the possibility of opening the windows to other passengers) and more frequent replacement of the refrigerant. In the case of an electrical system the most important causes are the lack of control over the battery level and improper use of vehicles by drivers. Proposed solutions include, among others, periodic training of employees increasing awareness and daily diagnostics of vehicle fleet by a qualified personnel. The last to be taken into consideration is the braking system, which is inefficient braking the vehicle. The reasons for this are the weak technical service of vehicles before leaving the depot. It is therefore necessary to daily service vehicles by checking individual fluids, condition of brake pads, and discs.

The next, fifth stage of the model is the implementation of improvements and validation of their effectiveness, implemented using FMEA method. This method consists in calculating the Risk Priority Number (RPN), which is designated by the dependence [18]:

$$RPN = S \times O \times D \tag{2}$$

where S is severity, O is probability of occurrence, and D is detection.

To determine the probability of failure of the analyzed system P, the following relationship is used:

$$P\left(U'\right) = \frac{LU'}{LU} \tag{3}$$

where LU' is the number of types of damage of a given system for the type of bus under examination within 1 year and LU is total number of failures for the type of bus under examination within 1 year.

Figure 5 presents the probability of failure of each system in vehicles per 1000 kilometers driven. The highest probability of failure is related to the electrical system

Table 2: Proposed solutions for detected problems.

(a)

Type of problem	Causes of the problem	Suggested solutions
	Bodywork	
Corrosion of the body	Weak storage of vehicles	Heating garages in winter
		Storage of vehicles in well-ventilated and dry garages
	Inadequate maintenance	Frequent washing of vehicles
		After cleaning, protective measures for varnish protection
	Inadequate manufacturer's corrosion protection	Increased control services in search of rust fires
		Inspections of vehicles for paint defects and their protection if necessary
		Additional anti-corrosion protection of closed profiles, e.g. doors

(b)

Type of problem	Causes of the problem	Suggested solutions
	Engine with attachments	
Weak air supply	Defective air conditioning compressor	Do not turn on the air conditioning system with the windows open
		Before switching on the air conditioning, ventilate the vehicle
	Leaks in the air conditioning system	Periodic checking of the tightness of air conditioning system connections
		More frequent diagnosis of errors using the OBD II interface
	Too small amount of refrigerant every 2 years	Compulsory refrigerant exchanges every 1 year
	Faulty condenser	Periodic checking of the condenser for mechanical damage
	Electrical systems	
Problems with starting the engine	Defective starter	Replacement of damaged starter components
	Defective fuel systems	Instructing drivers with shorter start-up time
	Uncharged battery	Periodic checking of battery voltage
		Charging the battery when stationary
	Short circuit in electrical system	Connection of diagnostic equipment and detection of faults
	Too much battery load during engine start	Disconnection of unnecessary current collectors
	Unqualified personnel	Increased number of employee training
	Unawareness	Software systems supporting analysis of driving parameters
	Braking systems	
Weak braking	Aerated braking system	More frequent de-aeration of the brake system
		Control of brake fluid level by drivers
	Used brake fluid	More frequent change of brake fluid
		The use of brake fluids with better technical parameters
	Badly installed brake pads or discs	Additional training for mechanics
		Disciplining the drivers of the machine park
	Greasy brake pads or discs	Cyclic use of degreasing agents

(Mercedes-Benz O530 K Citaro 35%) and average 22% concern on failures in the brake system. The third-largest probability is the transmission system.

To define the number of defect risks the average value of all bus failures for individual systems was used, as shown in Figure 6.

For the determined average values of damage of individual systems, the appropriate number O (Table 3) is assigned. O is the probability of occurrence of a given damage in a predetermined or determined time interval [11, 18].

S is a dimensionless number denoting severity, which is an estimation of how the effects of a given damage affect

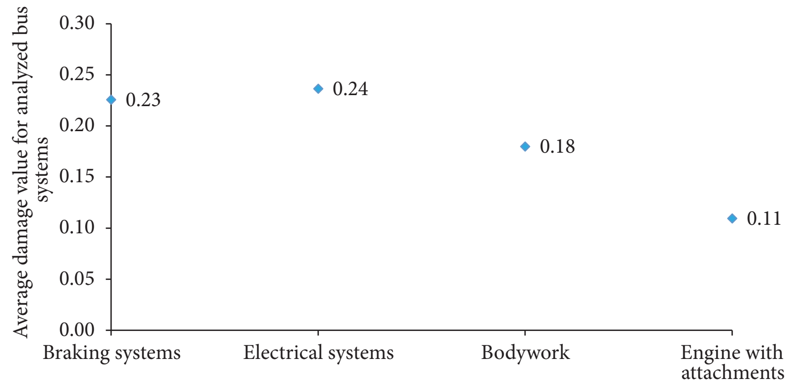


Figure 6: Average damage value for analyzed city bus systems.

Table 3: Failure mode occurrence related to frequency.

Failure mode occurrence	Frequency	Rating, O
Remote: Failure is unlikely	< 1/5000	1
Low:	1/5000	2
Relatively few failures	1/2000	3
Moderate: Occasional failures	1/1000	4
	1/500	5
	1/200	6
High:	1/100	7
Repeated failures	1/50	8
Very high:	1/10	9
Failure is almost inevitable	≥ 1/2	10

the use of a given system. In order to determine the severity for individual systems, the following evaluation was used (Table 4) [11, 18].

D means detection, i.e., determining the chance of identifying and eliminating a given damage before it hits the system or its use. Table 5 presents the evaluation criteria for determining the detectability for individual systems [11, 18].

After specifying the individual parameters S, O, and D, Table 6 shows the first FMEA analysis for the specified systems.

Such analysis is a valuable source of information for the manager of the operation of a public transport company, when choosing corrective measures. After the analysis, the target value of the Priority Risk Number (RPN) was determined and after analyzing the literature it was decided that the target RPN was set at RPN level of 240.

The next step is to check the effects of the proposed corrective measures, whether the RPN of each test system is less than 240; therefore four conditions must be fulfilled:

$$RPN > \mathrm{RPN}_{\text{BRAKING SYSTEM}} \quad (4)$$

$$RPN > RPN_{\text{ELECTRICAL SYSTEM}} \quad (5)$$

$$RPN > RPN_{\text{ENGINE WITH ATTACHMENTS}} \quad (6)$$

$$RPN > RPN_{\text{BODYWORK}} \quad (7)$$

If after the first FMEA analysis the values of the individual RPN's do not meet the above inequalities, the FMEA analysis with the subsequent corrective measures shall be repeated until the desired values are achieved. Before the corrective actions, all RPN values of each system exceeded the RPN = 240, which was also done and shown by the graph in Figure 7.

After corrective actions, FMEA analysis was again performed and the RPN values of individual systems were checked to see if they went under the below target value. Figure 8 shows a graph with RPN values for individual systems after the first FMEA analysis. It can be pointed out that for three of the systems the RPN value is below the target value (240). The greatest improvement was noted at the brake system, because the RPN value dropped from 810 to 180. In the case of the electrical system, the value decreased from 432 to 144, while in case of the body system the RPN decreased from only 324 to 140. However, further corrective actions for the 4th system (engine with attachments) are necessary.

Table 7 presents the second failure mode and effects analysis (FMEA) for engine with attachments systems and corrective actions for this systems. In turn, another results are presented in Table 8.

After performing the corrective action for the engine with attachments in the second FMEA analysis, it was found that the value of $\mathrm{RPN}_{\mathrm{EWA}}$ decreased to a value equal to only 98, which is the result of more than twice lower than that required. Finally, after all corrective actions, the RPN values were

$$RPN = \{98, 140, 144, 180\} \quad (8)$$

It was found that the improvement activities had the desired effect, as illustrated in Figure 9 showing a comparison of RPN values before and after corrective measures based on FMEA analysis.

The last (sixth) stage of the improved model for the exploitation of passenger vehicles is the QFD, which shows the relationship between customer requirements and the technical characteristics of products or services (Figure 10).

Table 4: Failure mode severity.

Severity	Criteria	Ranking
None	No discernible effect.	1
Very minor	The defect is irrelevant and the user will hardly feel its effects (perceived by less than 25% of users).	2
Minor	The defect is irrelevant and the user will hardly feel its effects (perceived by 50% of users).	3
Very low	A defect of medium importance, causing user dissatisfaction. Seen by the majority of users (about 75%).	4
Low	A defect of medium importance, causing user dissatisfaction. The user feels its effects and is a bit dissatisfied.	5
Moderate	A defect of medium importance, causing user dissatisfaction. The user feels its effects and is dissatisfied.	6
High	A defect of great importance, resulting in reduced system performance. User very dissatisfied.	7
Very high	Inoperative system (loss of the primary function).	8
Hazardous with warning	A defect of very high importance, affecting the safety of use and/or entails failure to comply with government regulations, with warning.	9
Hazardous without warning	A defect of very high importance, affecting the safety of use and/or entails failure to comply with government regulations, without warning.	10

Table 5: Failure mod detection evaluation criteria.

Detection	Criteria: likelihood of detection by Design Control	Ranking
Almost certain	The inspectors will almost certainly detect a possible defect and the subsequent damage.	1
Very high	A very good chance that the inspectors will detect a possible defect and the subsequent damage.	2
High	A high chance that the inspectors will detect a possible defect and the subsequent damage.	3
Moderately high	Moderately high chance that the inspectors will detect a possible defect and the subsequent damage.	4
Moderate	A moderate chance that the inspectors will detect a possible defect and the subsequent damage.	5
Low	Low chance that the inspectors will detect a possible defect and the subsequent damage.	6
Very low	Very low chance that the inspectors will detect a possible defect and the subsequent damage.	7
Remote	A small chance that the inspectors will detect a possible defect and the subsequent damage.	8
Very remote	A very small chance that the inspectors will detect a possible defect and the subsequent damage.	9
Absolutely uncertain	Inspectors will not detect and/or cannot detect a possible defect and subsequent damage. Or no system control.	10

4. Target Values of Exploitation of Passenger Transport Parameters

The QFD method is a way of "translating" opinions and needs of customers into a technical language, understandable in the company by designers, builders, and technologists. It serves to translate market requirements into conditions that an enterprise must meet.

The use of this method is caused by reflection, that the decisive factor standing behind the financial condition of the companies is the buyers of their products. Even if the product is correct from an engineering point of view, it does not have to provide economic success because it is determined by the consumer market, the customer.

Similar dependencies could be set for the vehicle designer and engineer having to build it. Based on the data above, a QFD diagram has been developed in the form of a "quality house", Figure 11.

The goal of a quality home is to set critical parameters and set their target values in such a way as to ensure success in the

Table 6: First FMEA analysis for individual systems.

Specificity defects	Effect	Cause	S	O	D	RPN	Corrective Action
Bodywork							
Corrosion of bus body	Dissatisfaction users Weakness of supporting structure of the bus	Wrong storage and maintenance of the vehicle	**4**	**5**	**9**	**324**	Improve the method maintenance and storage Make additional corrosion protection, in particular closed profiles
Engine with attachments							
Inefficient work of the air conditioning system	Too high temperature and air humidity in the bus, preventing comfortable traveling	Damaged compressor Leaks in the air conditioning system Insufficient amount of refrigerant	**7**	**9**	**7**	**441**	Regular servicing Don't turn on the air conditioning system while the windows open Replace the refrigerant every 1 year
Electrical systems							
Problems with starting the engine	Delays in commuting bus trips	Failed starter Uncharged battery Short circuit in electrical system Too thick engine oil during start-up	**8**	**9**	**6**	**432**	Replacement of damaged starter components Rechargeable batteries during stoppages The use of seasonal engine oils
Braking systems							
Inefficient braking	The bus driver is not able to brake hard enough in an emergency situation	Aerated braking system Badly fitted brake pads or discs	**10**	**9**	**9**	**810**	Frequent venting of the system and control condition of the brake fluid Additional training and disciplining their mechanics

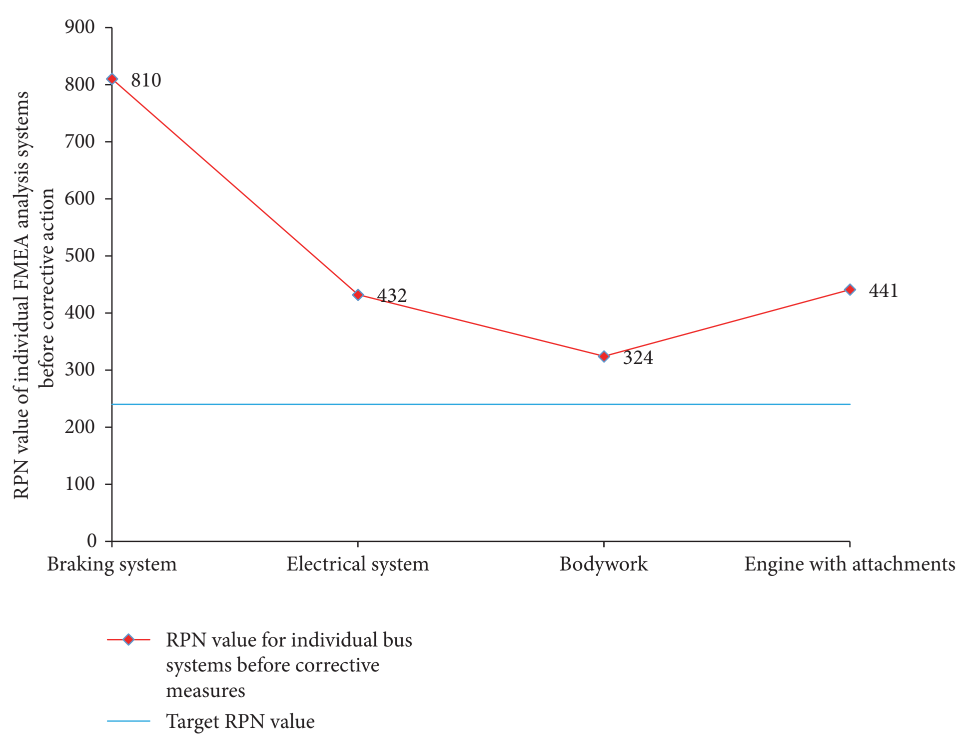


Figure 7: RPN value each of the bus systems before corrective action based on FMEA.

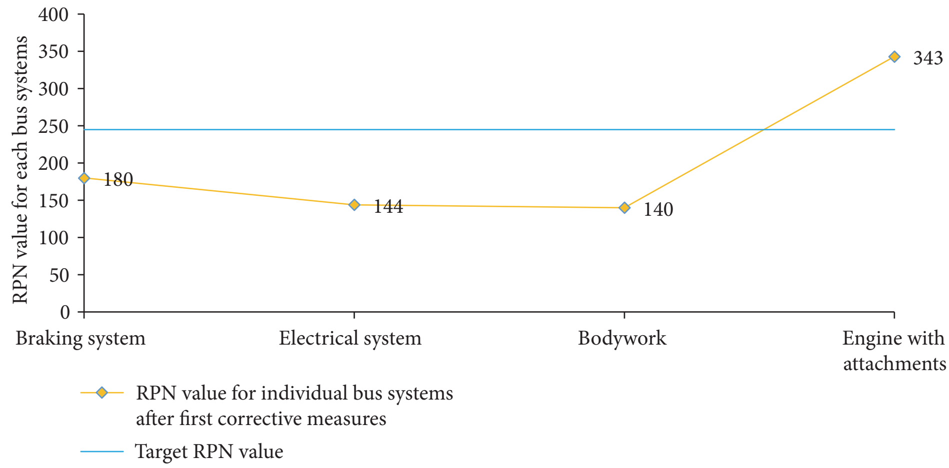


FIGURE 8: RPN value for each of the bus systems after the first phase of corrective action based on FMEA.

TABLE 7: Second FMEA analysis for the engine with attachments system.

Specificity defects	Effect	Cause	S	O	D	RPN_{EWA}	Corrective Action
Inefficient operation of the air conditioning system	Too high temperatures and humidity in the bus make it impossible to travel comfortably	Compressor damage Leaks in the air conditioning system Too little refrigerant	7	7	7	343	Ventilate the vehicle before turning on the air conditioner Periodic air tightness check

TABLE 8: Results after second FMEA analysis of the engine with attachments system.

Specificity defects	S	O	D	RPN_{EWA}	Further corrective action
Inefficient operation of the air conditioning system	**7**	2	**7**	**98**	No corrective actions

market for the services or products offered. In the presented case, 3 target parameters were defined:

(1) Servicing in the cycle 1 time per month for each of the buses.

(2) Driver training courses in the cycle 6 times per 1 year for each driver.

(3) Vehicle reliability at the average level of 1 failure per 2 weeks for each vehicle.

5. Conclusions

Based on presented study, the following conclusions were made:

(i) The process of exploitation of city buses in Wroclaw is not full correctly realized and requires improvement.

(ii) Based on the analysis of Pareto-Lorenz, it was stated that around 80% of all damage was generated by the half of investigated systems.

(iii) The proposed solutions to the problems in the various systems, based on the causes of their development and the Ishikawa diagram have brought measurable benefits in the FMEA method.

(iv) With the FMEA analysis, a reduction in the number of RPNs was achieved in the range of 57% to 78%, most already after the first phase of corrective action.

(v) Based on the QFD method, the relationships between customer requirements and the technical parameters of city buses were determined and 3 of them were diagnosed as critical parameters: servicing, driver training courses, and vehicle reliability.

In addition, one should choose the proper operating strategy, depending on the nature of the work of the vehicle. If sudden breakdowns that prevent the vehicle from operating properly will not cause additional losses such as lost earnings and loss of image, a reactive strategy can be used to repair after the failure; otherwise preventive strategies should be chosen, much more reasonable, that is, to prevent damage. Using the QFD method that allows to improve quality causes that a company dedicated to the well-known needs of the customer has a clear advantage over its competitors. Detailed knowledge about the current needs of customers allows

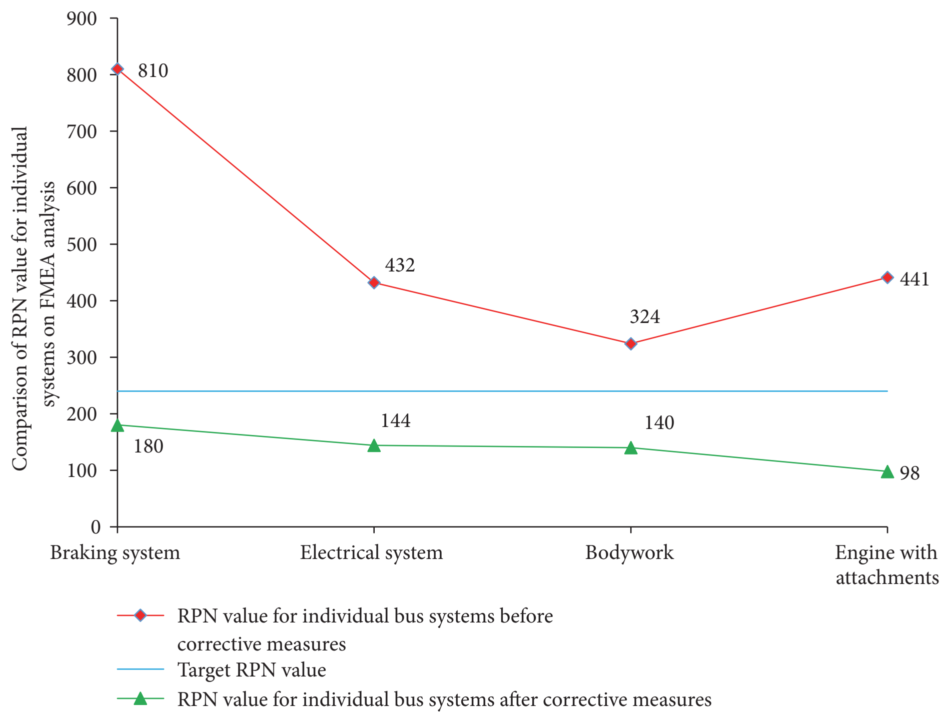


Figure 9: Comparison of RPN values for each of the bus systems before and after corrective actions based on FMEA analysis based on FMEA.

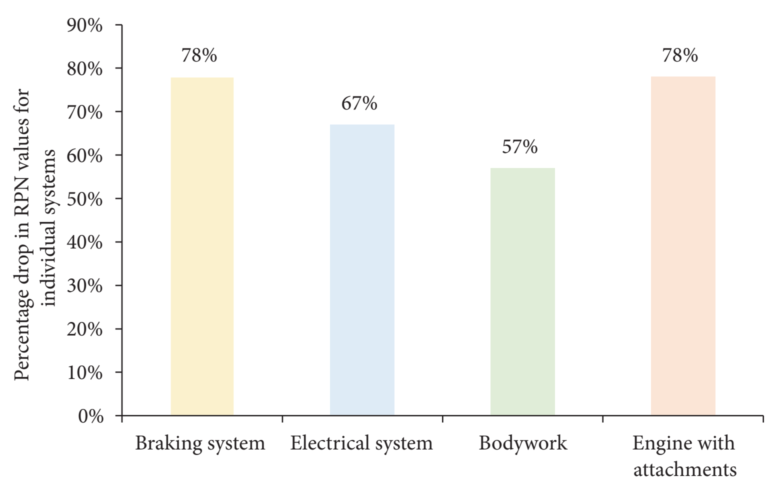


Figure 10: Percentage drop in RPN values for each of the bus systems.

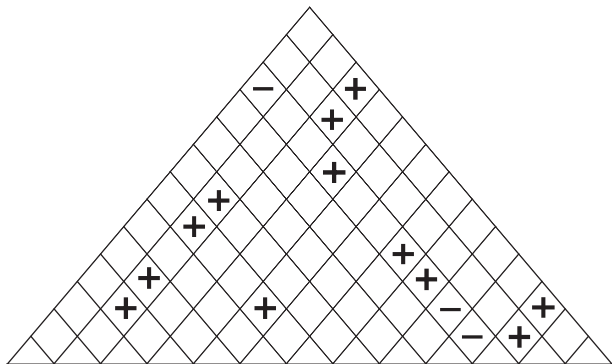
us to take action to ensure optimal satisfaction of them. When refining and modifying the undertaken activities, it is important for marketing of the company to remember to continually show its strong sides in order to provide the company with a competitive advantage.

At present, significant development of all types of quality improvement activities of processes or services is evident, due to increasing customer demands and ever-increasing competition.

Built analysis model and evaluation of the exploitation of passenger transport have been verified with actual data obtained from the MPK in Wroclaw. It can find practical use in other urban agglomerations, which would improve the operation of passenger transport.

Data Availability

The exploitation data used to support the findings of this study were supplied by MPK Wrocław under license and so cannot be made freely available. Requests for access to these data should be made to MPK Wrocław, bop@mpk.wroc.pl.



		accessories of the vehicle	climatic conditions in the vehicle	servicing	drivers training courses	disciplining drivers	modern technologies	washing & cleaning vehicles	quality od mechanics work	age of the vehicle	Service life of the vehicle	reliability of the vehicle	Adjustments and maintenance	daily service					
		↑	•	↑	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑					
working interior lightning	2	3		1			1		3	2	2	2	2	2		B	A		C
pleasant smell	5	1	3	2				3	1	1	1						C	A	B
smooth driving	8			1	3	3	1		1	1	1	1	1			A		C	B
cleanliness inside & outside	8		1					3					1	1			A	B	C
efficient heating	8		2	3					3	1	1	1	1				B	A	C
efficient air conditioning	8		2	3					3	1	1	1	1			A		B	C
fast driving	5			1	3	3			1	1	1	1			B	C			A
punctuality od arrivals and	9	1		1	3	3	1					1			B	C			A
optimal temperature	7		3	2	3							3	1			A		B	C
collision-free driving	9	3		1	3	2											A	B	C
fault-free driving	8			3					3	3	3	3	3	3			A	C	B
safe diving	8	3			3	3						2					A	B	C
quiet driving	5			1					1	1	1	3					A	B	C
easy to open windows	4	1		1				1	1	1	1	1	1			C	B	A	
working validators	3			1					1				1	1	C		A	B	
Technical Evaluation		75	76	141	138	108	19	48	108	105	111	122	74	39	1	2	3	4	5
Specification Target Value		as expected of users	21°C	1/month	6/year	if necessary	as many as possible	1/week	no mistakes at work	max 5 years	max 2 mln km	1 failure/2 weeks	2/week	before & after using vehicle					
Technical Difficulty (1-Low, 5-High)		4	2	5	2	1	4	3	4	4	4	4	2	3					
Importance Rating				1.	2.							3.							

A	B	C
320	351	393

Color	Description
	Customer Needs
	Importance to the customer
	Engineering Characteristics
	Engineering Characteristics & Customer Needs Correlations
	Technical requirements type
	Technical Evaluation
	Engineering Characteristics Correlations
	Competitive Evaluation
	Customer perceptions Rating
	Customer perceptions Results
	Specification Target Value
	Technical Difficulty
	Importance Rating (Critical parameters)

Figure 11: "Quality home" the operation of city buses.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Theoretical Comparison of the Effects of Different Traffic Conditions on Urban Road Traffic Noise

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Road traffic noise is one of the most relevant sources in the environmental noise pollution of the urban areas where dynamics of the traffic flow are much more complicated than uninterrupted traffic flows. It is evident that different traffic conditions would play the role in the urban traffic flow considering the dynamic nature of the traffic flow on one hand and presence of traffic lights, roundabouts, etc. on the other hand. The main aim of the current paper is to investigate the effect of different traffic conditions on urban road traffic noise. To do so, different traffic conditions have been theoretically generated by the Monte Carlo Simulation technique following the distribution of traffic speed in the urban roads. The "ASJ RTN-Model" has been considered as a base road traffic noise prediction model which would deal with different traffic conditions including steady and nonsteady traffic flow that would cover the urban traffic flow conditions properly. Having generated the vehicles speeds in different traffic conditions, the emitted noise (L_{WA}) and subsequently the noise level at receiver (L_A) were estimated by "ASJ RTN-Model." Having estimated L_{WA} and L_A for each and every vehicle in each traffic condition and taking the concept of transient noise into account, the single event sound exposure levels (*SEL*) in different traffic conditions are calculated and compared to each other. The results showed that decelerated traffic flow had the lowest contribution, compared to congestion, accelerated flow, free flow, oversaturated congestion, and undersaturated flow by 16%, 14%, 12%, 12%, and 10%, respectively. Moreover, the distribution of emitted noise and noise level at receiver were compared in different traffic conditions. The results showed that traffic congestion had considerably the maximum peak compared to other traffic conditions which would highlight the importance of the range of generated noise in different traffic conditions.

1. Introduction

Highly industrialized living style of modern societies has produced a dramatic impact on the environment [1]. Nowadays, the environment noise and emission [2] have become a worldwide problem and the environmental impact control is one of the most important problems in the urban areas [3]. It is reasonable to affirm that, in urban areas, road traffic noise is the most relevant source [4] since airports are usually placed outside the downtowns and railways are usually designed to move out from the center of the cities [5] and rarely cross the residential districts [6]. Furthermore, in urban areas, the concentration of both road networks and city dwellers makes of traffic flow the main culprit of noise annoyance, which has to be precisely estimated and treated through relevant road traffic mitigation [7]. Although the road noise is not usually loud enough to cause hearing problems, continuous exposure to unacceptable noise levels can create the adverse effects on health [8]. Moreover, environmental noise exposure is associated with annoyance [9, 10], sleep disturbance [11], cognitive ability in schoolchildren [12], and health impacts, especially cardiovascular conditions [13]. Exposure to environmental noise is pervasive and increasing in terms of road traffic noise and the reduction of the night-time quiet period [14]. Traffic-related noise is one of the major environmental impacts of roadways [15] and is said to account for over 1 million healthy years of life lost annually to ill health and may lead to a disease burden that is second only in magnitude to that from air pollution [16]. According to the WHO, the environment noise costs societies 0.2%-2.0% of the gross domestic product [17].

Therefore, urban road traffic emission and noise should be included in the economic evaluation of an urban road traffic policy [18] since different traffic conditions, as consequence of these policies, might have a considerable contribution in the urban road traffic noise emission which would have a significant impact on the gross domestic product of the societies. Noise prediction is one of the vital tools for city planners for noise abatement and control [19]. Traffic management can be a very effective policy to fight against urban traffic noise [20, 21] which is increasingly implemented in European [22] noise reduction projects. By taking a wide look at the literature, mostly, noise impacts of traffic management policies have been measured/investigated by conducting the on-field studies [23]. The current research instead seeks to provide a theoretical comparison environment in which the average impact of different traffic conditions on road traffic noise emission would be compared. Generally, the estimation of the noise emissions generated by road traffic requires both a noise emission model that captures the impact of vehicle kinematics, namely, speed and acceleration, on sound power levels, and an accurate estimation of the kinematic variables of interest in the area under study [24]. There are various models developed recently in order to evaluate the road traffic noise emissions. For instance, the Federal Highway Administration Traffic Noise Model (FHWA TNM) of USA [25] predicts the hourly equivalent sound level of the i^{th} class of vehicles based on the reference energy mean emission level of the i^{th} class of vehicles which refers to the maximum sound level emitted by a vehicle pass-by at a reference distance of 15 (m) through a series of adjustments as follows.

$$L_{eq}(h)_i = \left(\overline{L_0}\right)_{Ei} + \Delta_{f(i)} + \Delta_d + \Delta_l + \Delta_s \tag{1}$$

where

$L_{eq}(h)_i$ is hourly equivalent sound level ($dB(A)$)

$(\overline{L_0})_{Ei}$ is reference energy mean emission level ($dB(A)$)

$\Delta_{f(i)}$ is traffic flow adjustment

Δ_d is distance adjustment

Δ_l is length of the roadway adjustment

Δ_s is shielding adjustment

The CoRTN (Calculation of Road Traffic Noise) model of the United Kingdom estimates the A-weighted sound pressure level that is exceeded for 10% of the measurement period at a reference distance of 10 (m) away from the nearside carriageway edge as follows [26].

$$L_{10} = 42.2 + 10\log_{10} q + \Delta_f + \Delta_g + \Delta_p + \Delta_d + \Delta_s + \Delta_a + \Delta_r \tag{2}$$

where

L_{10} is A-weighted sound pressure level that is exceeded for 10% of the measurement period (dB(A))

q is total hourly flow (veh/hr) calculated at a reference distance of 10 (m) at an average traffic speed of 75 (km/h)

Δ_f is traffic flow adjustment

Δ_g is gradient adjustment

Δ_p is pavement type adjustment

Δ_d is distance adjustment

Δ_s is shielding adjustment

Δ_a is angle of view adjustment

Δ_r is reflection adjustment

The HARMONOISE (Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise) model [27] of the European Union is defined based on two sound power values for different vehicle categories as follows.

$$L_{WR}(f) = a_R(f) + b_R(f)\log\left(\frac{V}{V_{ref}}\right) \tag{3}$$

$$L_{WP}(f) = a_P(f) + b_P(f)\log\left(\frac{V - V_{ref}}{V_{ref}}\right) \tag{4}$$

where

$L_{WR}(f)$ is rolling noise generated by tire-road interaction and aerodynamic drag (dB(A))

$L_{WP}(f)$ is propulsion noise generated by the powertrain and the exhaust (dB(A))

V_{ref} is 70 (km/h)

$a_R(f)$, $b_R(f)$, $a_P(f)$, and $b_P(f)$ are given coefficients in $1/3^{rd}$ octave bands in frequency range 25 to 10 kHz

The ASJ RTN-Model (Acoustical Society of Japan Road Traffic Noise prediction model) considers a single vehicle as an omnidirectional point source passing along the road under consideration and predicts the noise emitted by each vehicle in different categories as a function of the vehicle speed in different traffic conditions (steady and nonsteady traffic flow, acceleration, and deceleration running condition) as follows [28].

$$L_{WA} = a + b\log(V) + c \tag{5}$$

where

L_{WA} is A-weighted sound power level (noise emitted by each vehicle) (dB(A))

V is vehicle speed (km/h)

a and b are regression coefficients

c is correction term for road conditions (pavement type and road gradient)

Furthermore, noise propagation from the i^{th} source position to the prediction point will be predicted as follows.

$$L_{A,i} = L_{WA,i} - 8 - 20\log r_i + \Delta L_{cor,i} \tag{6}$$

where

$L_{A,i}$ is A-weighted sound pressure level (noise level at receiver) (dB(A))

r_i is direct distance from the i^{th} source position to the prediction point (m)

$\Delta L_{cor,i}$ is correction for diffraction, ground effect, and atmospheric absorption (dB(A))

The main aim of the current research is to investigate the contribution of different traffic conditions in noise emission of the urban road traffic flow by preparing a theoretical comparison in which each traffic condition would generate road traffic noise independently. In the current study, different traffic conditions have been represented by the distribution of traffic speed in that traffic condition obtained by on-field data collection. It is worth to mention that the role of speed distribution on road traffic emission [29] and noise has been investigated in the literature. For instance, the effects of speed distributions on the Harmonoise model predictions have been investigated by [30]. They assumed when traffic is freely moving the speed distribution of a given category of vehicle approximates to a normal distribution. It is a very general assumption and they did not consider the situation in which the traffic flow freely moves but it is close to the capacity. They examined the errors in noise prediction which would result if the mean speed was used for prediction purposes rather than the actual speed distribution. They pointed out that it is likely that the assumptions concerning a normal distribution are not so robust due to the potential periods of congested traffic so that the estimates of standard deviation could be misleading. Also, due to the lack of data at the individual level, they have roughly assumed some other distributions for the other simple traffic conditions. The main difference of this paper with our paper is that we have investigated the effect of different traffic conditions based on the actual (fitted to empirical data) speed distributions adapted to the empirical traffic speed data obtained by the on-site traffic data collection in the city of Budapest, Hungary. In 2013, Iannone et al. [31] studied the influence of speed distribution on road traffic noise prediction. In their study, they investigated the effect of speed distribution (different speed distributions were simulated following the same average speed, 70 (km/h) and standard deviation, 10 (km/h)) on road traffic noise prediction using the "Micro to Macro" approach that adopts the single vehicle noise emission. The random extraction of the speed allows running the model also when single vehicle speed data are not available. In the current paper, the effects of different traffic conditions (different speed distributions and different speed specifications obtained by empirical data collection in city of Budapest) on urban road traffic noise were theoretically compared to each other using the Japanese reference noise model which is calibrated for different traffic conditions.

A majority of the researches in dynamic road traffic noise prediction topic considered the microscopic traffic flow characteristics (speed, acceleration, etc. of each and every single vehicles) instead of the macroscopic traffic flow characteristics (average parameters of the entire traffic flow) as the main element of the road traffic dynamics for noise prediction [24, 32, 33]. In the current paper, different traffic conditions have been theoretically generated based on the distribution of vehicles speed on that traffic condition. Furthermore, the reference road traffic noise model of Japan, the ASJ RTN-Model, has been selected as a base road traffic noise prediction model due to the fact that it is calibrated for both steady and nonsteady traffic flow (adapted for urban condition). Moreover, this model is also calibrated for acceleration and deceleration running conditions which would be appropriate in predicting the road traffic noise emissions close to the intersections. Apart from these, the base of the model is directly dependent on the speed of vehicles which is the considered characteristic of different traffic conditions in this research.

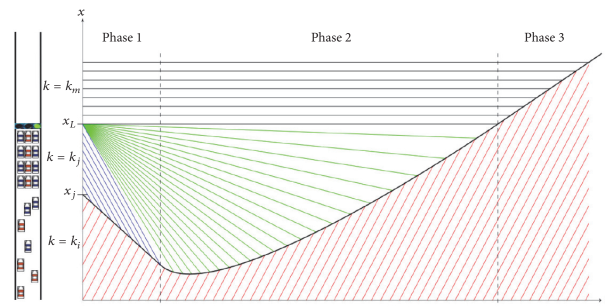

Figure 1: Characteristic diagram for traffic moving at a traffic light.

The rest of the paper is organized as follows. In Section 2, at first, different traffic conditions have been theoretically generated according to the distribution of vehicles speed in different traffic conditions and then the generated road traffic noise in each traffic condition is estimated using the ASJ RTN-Model. The estimated road traffic noises in different traffic conditions have been compared and discussed in terms of magnitude and continuity in Section 3. Finally, the paper is concluded in Section 4.

2. Methodology

The main aim of the current research is to compare the effects of different traffic conditions on urban road traffic noise. To do so, a field measurement campaign (manual video recording) has been done by the Stipendium Hungaricum (2016-2017/MSc) transportation engineering students in the two-lane Villnyi street and Karolina street intersection in Budapest, XI district, Hungary, during the entire day. Six different traffic conditions (scenarios) have been defined based on the recorded videos. The defined scenarios are theoretically explained here using a theoretical representation of a characteristic diagram for traffic moving at a traffic light when it turns to green as shown in Figure 1. The condition in which the traffic congestion would not be disappeared in a cycle (exceeds the capacity) is considered as oversaturated congestion. This is the region $x_j \leq x < x_L$ in Figure 1 where density is close to Jam density (k_j). The undersaturated flow is considered when the traffic is close to the capacity (and will be discharged in a cycle) in the region $x < x_j$ where traffic is flowing with the density lower than optimal density ($k_i < k_m$), as the flow is not unimpeded. The free

Table 1: Specifications of traffic speed in different traffic conditions.

Traffic condition	Fitted speed distribution	Minimum speed (km/h)	Maximum speed (km/h)	Average speed (km/h)	SD of speed (km/h)
Over-saturated congestion	Exponential distribution	1	15.5	10.37	2.74
Under saturated flow	Normal distribution	25	55	38.14	6.46
Free flow	Log-normal distribution	35	55	47.18	5.5
Congestion	Gamma distribution	10	25	14.53	3.91
Accelerated flow	Beta distribution	1	45	27.41	13.15
Decelerated flow	Chi-square distribution	1	35	18.76	11.82

flow traffic is considered when there are a few numbers of vehicles in the street (much lower than the capacity) in the region $x < x_j$ where traffic is flowing with the density lower than optimal density ($k_i < k_m$), as the flow is not unimpeded. The deceleration process is considered in the condition where traffic flow is getting closer to x_j (where the shockwave, black curve, travels backward through the traffic in phase 1 shown in Figure 1). When the traffic light turns green, vehicles are able to leave the light entirely unimpeded, so the density would be equal to optimal density ($k = k_m$) and obviously flow would be in its maximum. This condition is considered as the acceleration process in which the shockwave slows down and starts to move back towards the traffic light (phase 2). The condition in which traffic light turns to green but the intersection is not completely empty yet is considered as congestion.

Having collected the speed of vehicles in different traffic conditions, the distribution of speed in these traffic conditions was estimated by the Maximum Likelihood Estimation method as follows.

$$L(\theta) = \prod_{i=1}^{n} f(x_i \mid \theta) \quad (7)$$

where

x_i is observed traffic speed (km/h)

$f(\cdot \mid \theta)$ is density function of the candidate parametric distribution

Having estimated different candidate parametric distributions for traffic speed in different traffic conditions based on (7), the candidate distributions were compared to each other by three goodness-of-fit tests (Kolmogorov-Smirnov, Cramer-von-Mises, and Anderson-Darling) in order to find best-fitted speed distribution in each traffic condition as follows.

$$KS : \sup \left| F_n(x) - F(x) \right| \quad (8)$$

$$CvM : \int_{-\infty}^{\infty} \left(F_n(x) - F(x)\right)^2 dx \quad (9)$$

$$AD : n \int_{-\infty}^{\infty} \frac{\left(F_n(x) - F(x)\right)^2}{F(x)\left(1 - F(x)\right)} dx \quad (10)$$

where

F_n is empirical cumulative distribution function of the vehicles speeds

F_x is fitted theoretical parametric distribution

Apart from these three goodness-of-fit tests, two classical penalized criteria (Akaike and Bayesian information criteria) based on the log-likelihood were further considered to tackle the overfitting problems as follows.

$$AIC : 2k - 2\ln\left(\hat{L}\right) \quad (11)$$

$$BIC : \ln(n)\, k - 2\ln\left(\hat{L}\right) \quad (12)$$

where

k is number of estimated parameters in the model

$\hat{L}$ is maximum value of the likelihood function for the model

n is number of observations

The best-fitted distributions to the traffic speed in different traffic conditions along with the statistical specifications of the traffic speed in different traffic conditions are shown in Table 1.

Taking Table 1 into account, one would find out that the fitted distributions are all unimodal distributions. It should be highlighted that, in the current study, a homogeneous traffic flow (passenger cars) has been considered in both data collection and simulation phases. Therefore, single-mode distributions (fitted unimodal distribution) have been considered to simulate traffic speed in different traffic conditions since the literature suggests considering bimodal and multimodal distributions while there is a heterogeneity in traffic flow [34]. There is a lot of research that has examined distribution models for motorized vehicle speed data in uncongested traffic condition. On one hand, [35, 36] found that, for lightly trafficked two-lane roads where most vehicles are traveling freely, car speeds measured in time are approximately normally distributed. Also, Minh et al. mentioned that speed distribution would follow normal distribution on the urban roads, 2005 [37]. From the other hand, log-normal distribution has been considered for modeling speed data [38, 39] since it offers the advantage that the same functional form is retained when the time speed distribution is transformed into a space-speed distribution and avoids the theoretical difficulty of the negative speeds given by the infinite tails of

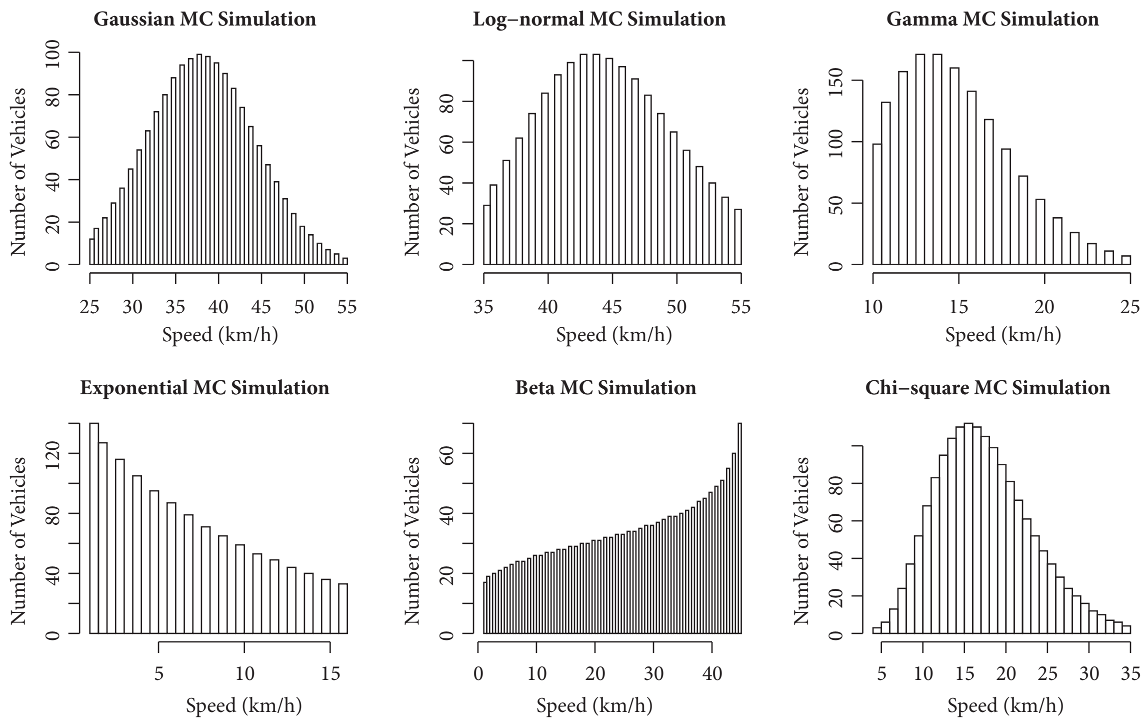

FIGURE 2: Random speed generation by Monte Carlo (MC) Simulation.

the normal distribution. In regard to log-normal distribution, Haight and Mosher [40] considered log-normal distribution since the speed data could be well represented by log-normal distribution in that study. Furthermore, [41, 42] suggested considering log-normal speed distribution for traffic speed simulation. Considering the fundamental relationship of the traffic flow, in the current study, the log-normal distribution is fitted better to the collected traffic speed in free flow condition (the condition in which much lower vehicles than the capacity were available in the roadway) and normal distribution is fitted better to the traffic speed in undersaturated flow condition (close to capacity condition).

2.1. Simulation of Different Traffic Conditions. In order to study the effect of different traffic conditions on road traffic noise emission, these traffic conditions were theoretically simulated by Monte Carlo (MC) simulation technique using the specifications of traffic speed in different traffic conditions shown in Table 1. It should be highlighted that the number of vehicles was considered to be constant (1600 vehicles) in each traffic condition in order to release the effect of traffic flow on further road traffic noise estimation. The randomly generated vehicles speeds which would represent the speed of vehicles in different traffic conditions are shown in Figure 2.

2.2. Road Traffic Noise Estimation. Having simulated the traffic speed in different traffic conditions theoretically, the A-weighted sound power level, L_{WA}, which would represent noise emitted by each single vehicle was calculated based on (5) in which the entire traffic flow has been considered to be in the same classification (passenger cars) with the same engine rotational speed, the same engine load, the same road pavement type, and the same road geometry in order to release the effect of determinants other than traffic condition on emission estimation.

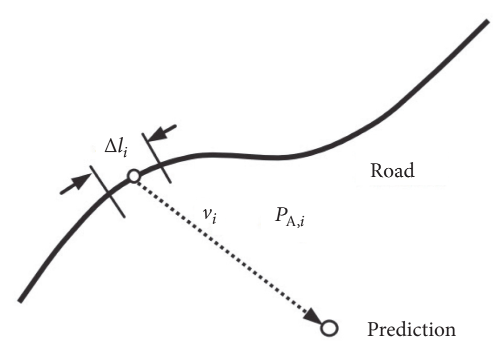

FIGURE 3: Sound propagation from a sound source to a prediction point [28].

The calculated L_{WA} for each vehicle is further considered as the basis of sound propagation as suggested by [28] and shown schematically in Figure 3 in which $P_{A,i}$ is the A-weighted sound power, $\Delta l_i(m)$ is the length of theoretical road, and v_i (km/h) is the running speed of vehicle.

Hence, the A-weighted sound pressure level, L_A, which would represent the noise level at receiver was calculated based on (6) considering the same distance from the source position to the prediction point (20 (m)), and the same $\Delta L_{cor,i}$ for the entire traffic conditions in order to release the effect of determinants other than traffic condition on sound propagation estimation. Moreover, it is worth to mention that a representative point (fixed point source) has been set

Table 2: Theoretical upper and lower boundaries of traffic noise in different traffic conditions.

Traffic condition	Min L_A $(dB(A))$	Max L_A $(dB(A))$	Min L_{WA} $(dB(A))$	Max L_{WA} $(dB(A))$
Over-saturated congestion	47.97	60.02	82	94.04
Under saturated flow	54.31	64.59	88.33	98.61
Free flow	58.7	64.59	92.72	98.61
Congestion	57.97	61.95	92	95.97
Accelerated flow	47.97	64.51	82	98.53
Decelerated flow	42.38	58.7	76.4	92.72

at the center point of the theoretical road section. In this case, the A-weighted sound power level L_{WA} emitted from the source (the vehicle) is set, and the A-weighted sound pressure level at the prediction point is calculated by applying a formula based on geometrical spreading (inverse-square law). It should be underlined that setting the fixed point source at the center point of the theoretical road section might result in an overestimation of the noise level. In the current research, this overestimation has been neglected due to the fact that a theoretical comparison platform has been provided such that the effects of different traffic conditions on urban road traffic noise have been theoretically compared to each other.

Having calculated the A-weighted sound power level and A-weighted sound pressure level received at the receiver from each and every vehicle, the single event sound exposure level (a constant sound level which has the same amount of energy in 1 second as the original noise level) of the vehicles is calculated as follows:

$$L_{AE} = 10 \log \left(\frac{1}{T_0} \sum_i 10^{L_{A,i}/10} . \Delta t_i \right) \tag{13}$$

where

T_0 is 1 s (the reference time)

$L_{A,i}$ is A-weighted sound pressure level in the i^{th} section (dB(A))

Δt_i is the time when the sound source exists in the i^{th} section (s)

The calculated sound exposure level of the entire traffic flow in each traffic condition is summed up according to [28], in order to calculate the total theoretical sound energy emitted from the traffic flow in each traffic condition. Since the point source has been considered to be fixed in the current study, choosing the sound exposure level parameter would help to (to a certain extent) overcome the overestimation of energy. This is due to the fact that we consider the energy in 1 second, with little variations. In general, considering the sound exposure level for calculating the total sound energy is more preferred for the situations we are facing the transient noise (e.g., an aircraft fly-over or a vehicle drive-by). These situations often result in wide variations from background noise to maximum level and if only the maximum level is reported, information on the duration of the noise (an important feature for rating annoyance) is lost. This also makes it difficult to compare between rapid and slow events and to combine different events for noise prediction purposes [43]. It should be highlighted that sound exposure level is numerically equivalent to the total sound energy.

3. Results and Discussion

Table 2 shows the theoretical upper and lower boundaries of the emitted noise (sound power level (dB(A)), L_{WA}) and its propagation (sound pressure level (dB(A)), L_A) considering 20 (m) distance from the source position in each traffic condition. Having estimated the noise emitted by running vehicles in different traffic conditions, L_{WA} $(dB(A))$, the noise level at receiver considering 20 (m) distance, L_A $(dB(A))$, is calculated based on (6). The theoretical relationship between speed ranges and sound pressure level in different traffic conditions were compared to each other in Figure 4 considering the same number of vehicles (1600 vehicles) in each scenario. By taking a wide look at Figure 4, one can simply find out that the vehicles in free flow condition have emitted sound pressure level in higher ranges compared to the other traffic conditions. It seems to be logical since the range of traffic speed in free flow condition is the highest among the other conditions (35 (km/h) to 55 (km/h)) based on Table 1. Also, taking the decelerated traffic flow into account, it is clear that the vehicles emitted sound pressure in a wider range compared to the other traffic conditions. It should be highlighted that, considering the speed-sound pressure level relationship of decelerated flow in Figure 4, the vehicles with the speeds lower than 10 (km/h) have emitted the same sound pressure level as the vehicles with the speed of 10 (km/h). This is due to the fact that, in deceleration running condition, the sound power level at speed of 10 (km/h) is applied at speeds of less than 10 (km/h) according to [28].

Figure 4 suggests the need for considering the dynamics of traffic flow in economic investigations of traffic/transportation policies. For instance, although the vehicles in free flow condition would have the higher sound pressure level compared to the other traffic conditions, they would pass the roadway faster than the vehicles in congestion or any other traffic conditions defined in Figure 1. Therefore, the overall generated single event sound exposure level in different traffic conditions has been considered for a theoretical comparison platform. Since the vehicles in decelerated traffic flow emitted sound pressure in a wider range compared to the

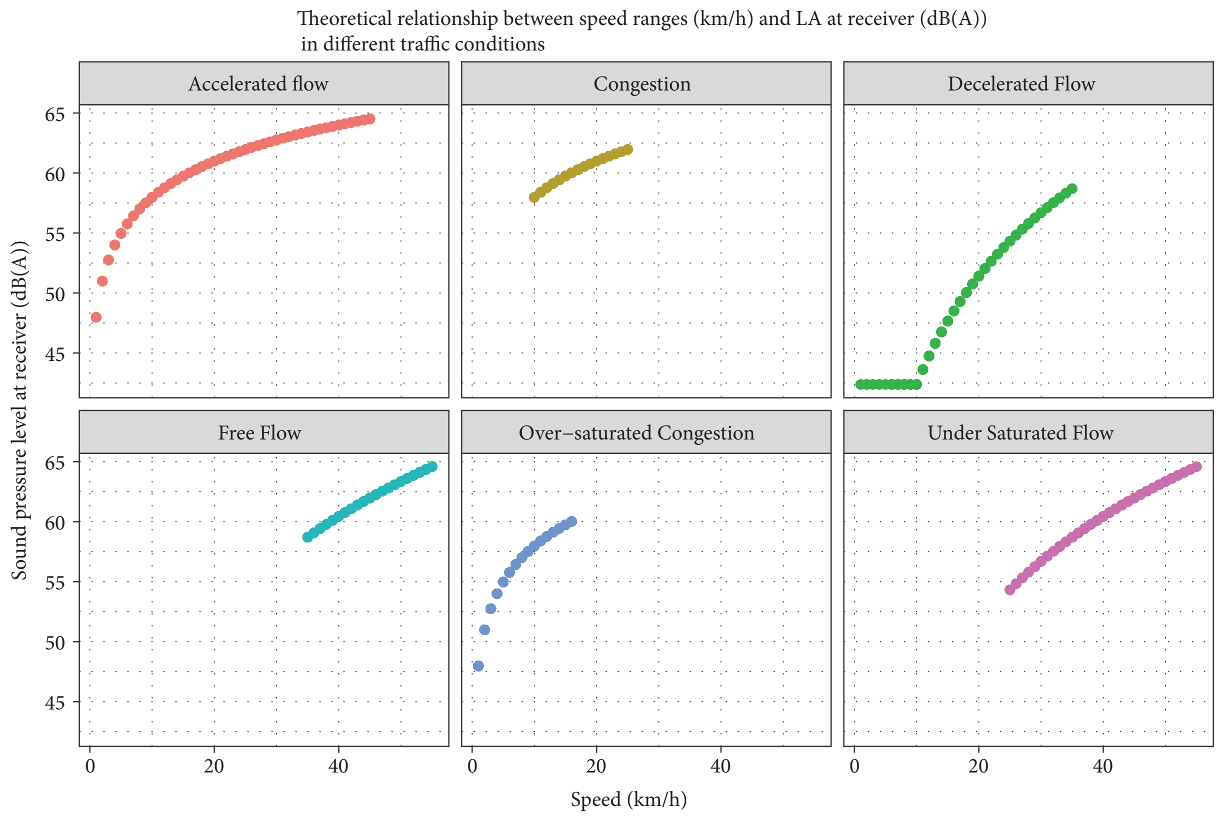

Figure 4: Theoretical relationship between speed ranges and the generated sound pressure in different traffic conditions.

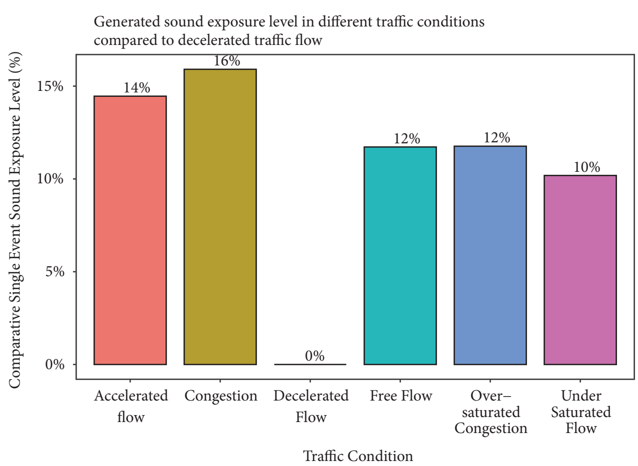

Figure 5: Comparing generated single event sound exposure levels in different traffic conditions.

other traffic conditions, the generated sound exposure level in each traffic condition has been compared to the generated sound exposure level in decelerated traffic flow in Figure 5.

Figure 5 clearly shows the fact that the vehicles in decelerated traffic flow would generate considerably lower sound energy compared to the other traffic conditions. Furthermore, comparing Figures 4 and 5 implies the fact that the dynamics of traffic flow which would generate different traffic conditions are of great importance in road traffic noise assessment. For example, although the free flow condition had the highest range of emitted sound pressure level, it has a lower sound exposure level compared to congestion and accelerated flow. Taking (13) into account, one would clearly understand that, apart from the emitted sound pressure level (L_A), the time when sound source exists in the roadway is of great importance in sound energy (sound exposure level) calculations. Therefore, compared to decelerated flow, traffic congestion, accelerated traffic flow, free flow, and undersaturated flow would theoretically generate more sound energy by 16%, 14%, 12%, and 10%, respectively.

It should be noted that the generated sound energy in decelerated flow condition is lower by 12% even compared to oversaturated congestion where cars have lower speed range (1 (km/h) to 15.5 (km/h)) compared to decelerated flow (1 (km/h) to 35 (km/h)) according to Table 1. This result might also confirm the suggestion of not just considering the speed ranges in different traffic conditions but also the dynamic nature of the traffic flow might have a considerable impact on the generated sound energy in traffic flow.

According to WHO, continuous exposure to unacceptable noise levels can create the adverse effects on health [8]. Moreover, the research evidence shows that the physiological effect of transportation noise on human sleep may depend more on the level and number of noise events in traffic streams than on energy equivalent measures [44, 45]. Therefore, not just the generated sound energy in road traffic is of great importance but also the distribution (continuity) of road traffic noise would be important. Hence, apart from the

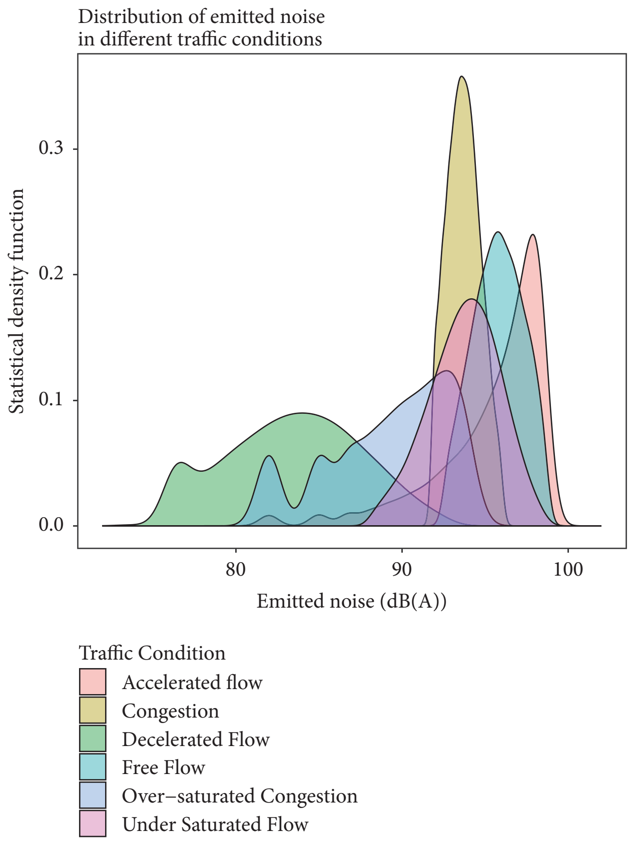

Figure 6: Comparing the distributions of emitted noise in different traffic conditions.

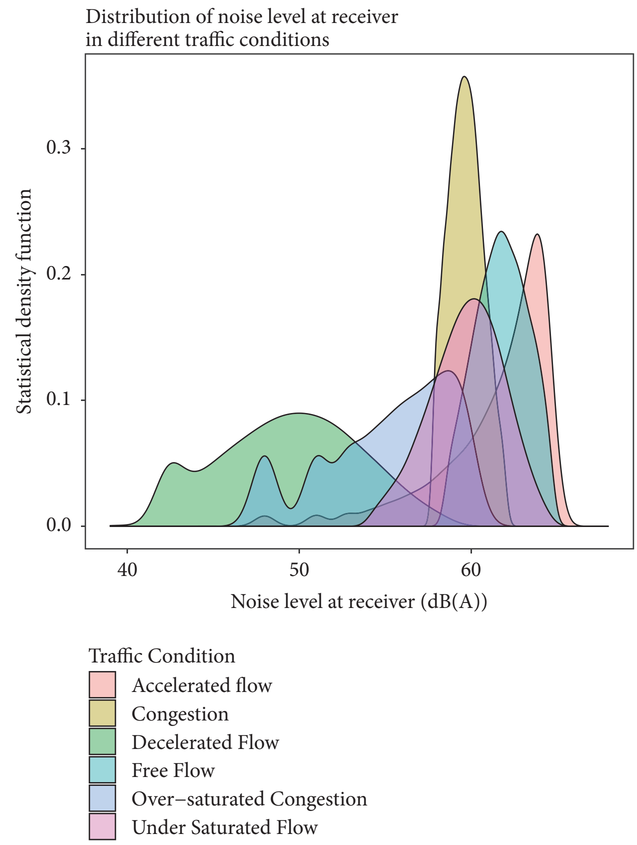

Figure 7: Comparing the distributions of noise level at receiver in different traffic conditions.

comparison of road traffic noise in different traffic conditions in terms of generated sound energy (Figure 5), they were compared in terms of continuity of road traffic noise by the means of density plots as shown in Figures 6 and 7, respectively. Most of the researches in this field suggested that by decreasing the speed rate the road traffic noise will be decreased. For instance, Ellebjerg proposed that noise abatement can be obtained through speed reduction [46]; furthermore Robertson et al. said that traffic calming policy ensures noise reduction since it forbids strong accelerations [47]. In fact, these statements are both true in terms of the generated sound pressure level such that the vehicles with the lower speeds would generate lower sound pressure level (see Figure 4 for illustration).

But the other parameter that needs to be considered in the evaluations is the number of noise events that are exceeded from the maximum thresholds since the physiological effect of transportation noise on human sleep may depend more on the level and number of noise events in traffic streams than on energy equivalent measures [44, 45]. Based on the abovementioned and considering Figures 6 and 7 which would clearly show the importance of the range of L_{WA} and L_A, it is evident that different traffic conditions, even with the same generated sound exposure level, might have different effects on their ambience. For instance, comparing Figures 5 and 7 implies the fact that the free flow condition and the oversaturated condition would generate the same amount of sound energy (sound exposure level) but the vehicles in free flow condition produce higher range of sound pressure level (58.7 (dB(A)) to 64.59 (dB(A))) compared to oversaturated congestion that ranges from 47.97 (dB(A)) to 60.02 (dB(A)). Moreover, Figures 6 and 7 show that the variations of the generated noise in congestion are the lowest compared to the other condition. Also, taking the traffic congestion into account, one would find out that it has, by far, the highest peak in both Figures 6 and 7. This is exactly due to the fact that the range of L_{WA} and L_A in traffic congestion (92 (dB(A)) to 95.97 (dB(A)) and 57.97 (dB(A)) to 61.95 (dB(A))) is shorter than the others based on Table 2. Therefore, the density plots would suggest paying attention to not just the maximum possible road traffic noise which may be caused by vehicle characteristics (speed, acceleration, etc.), but also the possible range of traffic noise which may be caused by nature of traffic condition in evaluation of the consequence of urban road traffic policies.

4. Conclusions

The rapid urbanization throughout the world extends the noise pollution, especially those induced by road traffic in the urban districts. Environmental noise exposure is associated with annoyance [9, 10], sleep disturbance [11], cognitive ability in schoolchildren [12], and health impacts, especially cardiovascular conditions [13]. In order to tackle these issues caused by road traffic, different traffic and transportation policies might be applied that would generate different traffic conditions. Hence, the effects of different traffic conditions on urban road traffic noise have been theoretically compared in this paper. The results show that when the traffic flow is in deceleration process it would theoretically generate lower sound energy compared to congestion, accelerated flow, free flow, and undersaturated flow by 16%, 14%, 12%, and 10%, respectively (see Figure 5). It should be noted that the generated sound energy in decelerated flow condition is lower by 12% even compared to oversaturated congestion where cars have lower speed range (1 (km/h) to 15.5 (km/h)) compared to decelerated flow (1 (km/h) to 35 (km/h)) according to Table 1. Furthermore, by taking a wide look at Figure 5, one would find out that free flow and oversaturated congestion would theoretically generate equal sound energy (sound exposure level) whereas they have different traffic speed ranges according to Table 1. In fact, these results would suggest that the emitted road traffic noise is the production of both traffic speed and dynamic nature of the traffic flow (pay attention to the range of the traffic noise in Table 2). Most of the researches in this field suggested that by decreasing the speed rate the road traffic noise will be decreased. For instance, Ellebjerg proposed that noise abatement can be obtained through speed reduction [46]; furthermore Robertson et al. said that traffic calming policy ensures noise reduction since it forbids strong accelerations [47].

Based on the abovementioned and considering Figures 6 and 7 which would clearly show the importance of the range of L_{WA} and L_A, it is evident that different traffic conditions, even with the same generated sound exposure level, might have different effects on their ambience. For instance, comparing Figures 5 and 7 implies the fact that the free flow condition and the oversaturated condition would generate the same amount of sound energy (sound exposure level) but the vehicles in free flow condition produce higher range of sound pressure level (58.7 (dB(A)) to 64.59 (dB(A))) compared to oversaturated congestion that ranges from 47.97 (dB(A)) to 60.02 (dB(A)). Moreover, Figures 6 and 7 show that the variation of the generated noise in congestion is the lowest compared to the other condition. Lastly, comparing the generated noises in different traffic conditions by density plots revealed the fact that not only is the generated sound exposure level in road traffic noise important but also the range of the generated noise in different traffic conditions is of significant importance. In this paper, the results showed that different traffic conditions might theoretically generate the same amount of noise (considering the equal number of vehicles) but in different ranges. Therefore, it might be concluded that the traffic condition that would generate the noise in the higher ranges (considering the distribution of generated noise in different traffic conditions) might have more negative effect on its ambience compared to the one that generates noise in lower ranges.

In the end, it should be highlighted that this research attempts to study neither the influence of junctions nor the influence of different driving patterns on noise emissions. But instead, it seeks to compare the average influences of different traffic conditions on urban road traffic noise in a theoretical environment. The scope for the future study is to calibrate the range of emitted noise in different traffic conditions in a real practice and build up a comparison environment based on the collected on-site values for further incorporation in the economic investigation of the road traffic policies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Integrating Bus Holding Control Strategies and Schedule Recovery: Simulation-Based Comparison and Recommendation

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In the absence of control strategies, headway fluctuation and bus bunching are commonly observed in transit operation due to the stochastic attributes such as travel time and passenger demand. Existing research on real-time control largely focused on developing operational tactics to maintain bus arrival regularity at stops without fully considering the effect of schedule recovery. This paper investigates the effect of bus driver behavior on bus holding control strategies and more specifically their effort in catching up with schedule in case of delay, i.e., schedule recovery. To this end, this paper first proposes a bus propagation model with capacity constraint to simulate the evolution of bus trajectories along a fixed route. It proceeds to explicitly incorporate both holding control actions and schedule recovery effect into the bus propagation model. Using simulation for a high-frequency bus line in Guangzhou, China, schedule- (SH) and headway-based holding (HH) control strategies are compared under various operational settings in the context of schedule recovery. These comparisons show that SH performs better under certain conditions, and SH generally benefits more from schedule recovery than HH. These results provide insights into the bus stop layout design and implementation of holding methods in the context of cruising guidance.

1. Introduction

Service reliability of public transport system is of great importance to passengers. Studies have shown that passengers value travel time reliability four times higher than they do to average travel time [1]. In the uncontrolled bus systems, buses are likely to bunch in the presence of stochastic travel time and demand, which is commonly observed in the peak hours. Bus bunching occurs when a number of buses arrive at a stop within an interval that is shorter than schedule headway or even together. Such phenomenon is undesirable for both passengers and the operator since it leads to unpredictable bus arrival times and additional waiting time at stops, which discourages passengers from choosing public transport.

A variety of operational tactics have been proposed to improve bus system performance in the literature, while holding control is the most commonly used [2]. The holding controlling approaches can be classified into three groups, including schedule-based control, headway-based control, and optimization-based control. They works by injecting slack time into the schedule at designated stops, in which the slack time refers to the amount of time that a task in a schedule can be delayed without causing a delay to subsequent tasks. The first two methods are triggered by bus arrival time and headway deviations, respectively, while the other one optimizes holding times through formulating a mathematical programming problem based on cost or time minimization. In this sense, the slack times are predetermined static settings for schedule-based control, whereas they are determined in real-time for headway- and optimization-based control. Osuna and Newell [3] investigated the holding problem at a single point for a cyclical route, in an attempt to minimizing the overall passenger waiting time. Hickman [4] developed an analytical model to determine the optimal holding time at a control stop along a bus route considering stochastic running times. Eberlein et al. [5] formulated the holding problem as a deterministic quadratic program with the availability of real-time information. Zhao et al. [6] studied the determination of optimal slack time under schedule-based control with the aim of minimizing the expected waiting time of passengers.

Daganzo [7] proposed a headway-based control scheme, where the holding times are dynamically determined by the information of the forward headway. It was found that the proposed method could achieve a faster speed and thus lower travel time compared to the schedule-based approach. Later, Xuan et al. [8] developed a family of control strategies by combining both the forward and backward headway information. Results show that such scheme can considerably reduce slack times and enhance headway regularity. This work was extended by Argote-Cabanero et al. [9] to be generalized to evaluate a bus corridor with multiple bus lines. Daganzo and Pilachowski [10] proposed an adaptive control scheme based on vehicle-to-vehicle cooperation, in which the bus cruising speed was adjusted in a real-time manner with the information of expected demand and vehicle spacing. They reported that the scheme yields regular headways with faster travel than the earlier control strategies. Delgado [11] developed a holding control policy in combination with boarding limit in an attempt to minimizing total delays on the transit corridor. Hernandez et al. [12] presented an extended model considering multiple bus line services. Recently, Sánchez-Martínez et al. [13] formulated a holding control model with dynamic running times and demand.

The variability in travel time is one of the central sources triggering bunching. Some efforts were taken to tackle the effects of exogenous variables on the travel time variability by employing machine learning models and predictive analytics that are able to explain such variability to learn about the behavior of a given fleet of vehicles. In this way, proactive control approaches could be generated that are able to prepare the system for delays or surges in demand before they reach a critical level. For example, Yu and Yang [14] used a support vector machine to predict the arriving status in the implementation of holding control. Moreira-Matias et al. [15] integrated the bus bunching prediction model into a real-time framework to mitigate bus bunching, of which the prediction output is used to select and employ corrective actions (holding and stop skipping). Nair et al. [16] presented real-time predictive analytics for bus bunching by using the real data in Miami-Dade Transit. Recently, Andres and Nair [17] presented a predictive-control framework to reduce bus bunching, which involves hierarchically related components including headway prediction and dynamic holding control. There are also literatures that investigate the exogenous factors affecting bus bunching, such as passenger arrival patterns (Fonzone et al. [18]) and the presence of common line (Schmöcker et al. [19]). Holding strategies have also been used for transfer synchronization. As direct and transfer demand are the mainstreams of transit networks [20], such problem is usually formulated as minimizing passenger waiting time or cost accounting for these types of passengers. Recently, Wu et al. [21] incorporated schedule-based holding control with a predefined time window into the bus schedule coordination design.

With the advances in connected vehicle technology and roadside detectors development such as time control points, the information of schedule deviations can be readily collected and informed to bus drivers. This provides new opportunities for transit operators with real-time schedule adherence status. Due to the travel time variability, both early and late arrivals can occur when compared to the reference timetable at the designated time control stops. One of the operational goals of a transit agency is to maintain buses on schedule. In reality, well-experienced bus drivers constantly adjust their speeds to keep their buses on schedule [22–25]. Figure 1 shows a potential way of realizing this goal using cruising guidance with colored bars that move up and down, such that drivers are able to vary their average speed to improve the schedule adherence. According to an empirical study conducted by a transit agency in the northeastern United States, schedule recovery effort can be observed on at least half of the segments on a bus route [22]. Recently, Liu et al. [26] proposed an inter-vehicle communication scheme to achieve a planned direct transfer. Two operational tactics were employed by using real-time information: speed control and holding at transfer point, of which speed control resembles schedule recovery behavior.

Schedule-based holding control are often employed when the bus arrives earlier than the scheduled arrival time. When a bus arrival is behind schedule, schedule recovery tactics could be deployed to support/guide the driver to catch up with the schedule at the next time control point. Unlike holding control that keeps buses at stops, the schedule recovery emphasizes speed adjustment between stops. This inter-stop control action can be utilized as complementary to holding control. Thus there may exist interactions between schedule recovery and holding control. The performance of bus scheduling is closely related to the dynamic motion of buses including driving behavior described by speed and acceleration. Therefore, schedule recovery behavior should be taken into consideration in the execution of holding control strategy. However, most of the existing literatures on holding control have focused on developing and evaluating the effectiveness of different action rules, largely neglecting the inherent effect of such schedule recovery driving behavior.

On the other hand, there is a set or "library" of feasible operational tactics to be used by transit operators. Among them, speed adjustment and vehicle holding are usually employed as combinatorial strategies. Speed adjustment, when applied in bus delay scenarios, resembles schedule recovery. For example, Nesheli et al. [27] used a combination of speed change control and headway-based holding control to reduce bus bunching. On a similar combination of strategies, Milla et al. [28] integrated holding and stop-skipping control based on fuzzy rules to minimize users' travel time. While headway-based and schedule-based control are two distinctive and most commonly implemented holding control methods, no performance comparison was made between them in the combinational design of operational tactics in the literature. Understanding the combined effect could help to design proper combinational tactics in response to varying traffic conditions.

The major focus of this paper is to compare the combined effect of schedule recovery and two different holding control approaches, so as to evaluate how cruising guidance technology and the resulting schedule recovery behavior affects

Figure 1: Cruising guidance on-board device surface (adapted from [9]).

the bus holding control strategies. This comparison should allow us to identify the scenarios for which the different holding control methods present advantages and highlight their respective strengths for further implementation in the context of cruising guidance technology. We have made an effort in this document to present both approaches with a common nomenclature. Our findings show that schedule recovery plays an important role in the design of bus holding control and that, for specific indicators, the optimal holding strategy transition will occur with certain level of schedule recovery effort and under certain conditions. We thus suggest the bus operators should select the most appropriate operation strategy that suits their operating conditions, which provides managerial insights into bus operational control. To the best of our knowledge, this is the first time that holding control strategies are compared in the context of schedule recovery.

The remainder of this paper is organized as follows. In Section 2, simulation frameworks are developed. In Section 3, performance measures are introduced to evaluate the performance of bus service. In Section 4, model experiments are performed and their practical implications are provided. Finally, the conclusions and future research directions are given in Section 5.

2. Modelling Approach

This paper is designed to investigate the effects of schedule recovery on the performance of holding control strategies, more specifically on the schedule-based and headway-based holding control. The main objectives are threefold: (a) develop an enhanced bus propagation and holding control models, which explicitly takes the schedule deviation and driving behavior into account; (b) compare the performance of the two holding control strategies under various operational settings in the context of schedule recovery; and (c) discuss the implementation issue for holding control with schedule recovery.

2.1. Assumption and Notations. Without loss of generality, the following assumptions are made:

(A1) Passenger arrival pattern relates directly to bus headways ([29]). In this paper passenger arrivals at bus stops is assumed to follow Poisson distributions. This assumption is reasonable on high-frequency routes, as has already been validated and commonly used by many researchers (e.g., [14, 30, 31])

(A2) The boarding process and the variability in link travel time are attributing factors to bus bunching.

(A3) Bus overtaking maneuvers are prohibited. This is reasonable since overtaking rarely occurs under the combined effect of holding and schedule recovery. This is also a common simplification in the literature (e.g., [13]). When overtaking is allowed, the bus order may change from stop to stop. Thus allowing overtaking requires structural changes to the model which has been left for another work.

(A4) Over the study-time horizon, passenger demand is assumed to be stochastic governing Poisson distribution, while bus running times vary at results from stochastic phenomena in the network.

2.2. Bus Propagation Model with Capacity Constraint. A bus motion model is comprised of three components: departures of buses, dwell times at stops, and link travels times. The arrival time of bus i at stop j is the departure time from stop $j-1$ plus the random link travel time between stop $j-1$ and j:

$$a_{i,j} = d_{i,j-1} + t_{i,j-1} \tag{1}$$

The uncontrolled bus departure time is determined by its arrival time and dwell time:

$$d_{i,j} = a_{i,j} + D_{i,j} \quad (2)$$

Following Liu et al. [32], the headway between bus i and the preceding one is assumed to be the gap between bus $i-1$ leaving stop j and bus i arriving stop j.

$$h_{i,j} = a_{i,j} - \overline{d}_{i-1,j} \quad (3)$$

where $\overline{d}_{i-1,j}$ stands for the previous departure time from the control point, which is equal to $d_{i-1,j}$ plus the corresponding holding time. $d_{i-1,j}$ is effectively equal to $\overline{d}_{i-1,j}$ without holding control.

Passenger arrival is assumed to be stochastic governing Poisson process, with the mean arrival flow equals to the product of the mean passenger arrival rate q_j and the headway $h_{i,j}$ of the bus with its leader. Therefore, the boarding demand for bus i at stop j is

$$B_{i,j} = P\left(q_j h_{i,j}\right) + l_{i-1,j} \quad (4)$$

The alighting demand is drawn from a binomial distribution, which is related to the bus load $L_{i,j}$ before arriving at stop j and its alighting percentage ρ_j.

$$A_{i,j} = Bi\left(L_{i,j-1}, \rho_j\right) \quad (5)$$

With vehicle capacity constraint, the actual number of boarding passengers is either the boarding demand or the remaining capacity, then we have

$$\begin{aligned}\overline{B}_{i,j} &= \min\left\{B_{i,j}, C - L_{i,j-1} + A_{i,j}\right\} \\ &= \min\left\{B_{i,j}, C - L_{i,j-1}\left(1-\rho_j\right)\right\}\end{aligned} \quad (6)$$

We assume that waiting passengers are loaded in a random fashion, which is appropriate when passengers mingle on waiting platforms. It is further assumed that each available space is equally likely to favoured by the waiting passengers, thus the boarding probability is the actual number of boarding passengers to the boarding demand, i.e., $\overline{B}_{i,j}/B_{i,j}$. Evidently, when the number of passengers who want to board exceed the remaining capacity, the probability is less than 1; otherwise, the probability is equal to 1. Therefore, the actual number of arriving passengers who are able to board is

$$\overline{B}'_{i,j} = \frac{\overline{B}_{i,j}}{B_{i,j}} P\left(q_j h_{i,j}\right) \quad (7)$$

Equations (6) and (7) are used to calculate the average waiting time; see Section 3.2.

Therefore, the number of leftover passengers is the difference between total boarding demand and the actual number of boarding passengers.

$$l_{i,j} = B_{i,j} - \overline{B}_{i,j} \quad (8)$$

The number of on-board passengers in bus i when it departs from stop j is related to the load before arriving the current stop and passenger flow at current stop.

$$L_{i,j} = L_{i,j-1} + \overline{B}_{i,j} - A_{i,j} \quad (9)$$

When the vehicle is not crowded ($L_{i,j}/C \le \varphi$, where $0 < \varphi < 1$ is a constant), passenger boarding and alighting take place simultaneously in a front-on rear-off policy. Thus the bus dwell time at the stop is estimated as the maximum time between the boarding and alighting time, plus the open and close door time.

$$D_{i,j} = \max\left\{b\overline{B}_{i,j}, \alpha A_{i,j}\right\} + \tau \quad (10)$$

where φ is a threshold of in-vehicle crowding degree. τ is the open and close door time. b and α represent the average boarding time and alighting time for passengers.

Note that the link travel time extracted from GPS data includes the acceleration and deceleration time.

If the vehicle is crowded, i.e., $\varphi < L_{i,j}/C \le 1$, the passengers would need more time to board and alight, and the dwell time is

$$D_{i,j} = \gamma \max\left\{b\overline{B}_{i,j}, \alpha A_{i,j}\right\} + \tau \quad (11)$$

where γ is the crowding coefficient, $\gamma > 1$.

2.3. Bus Holding Control with Schedule Recovery. When real-time holding control is in place, the bus departure time may be modified according to the control policy. This inherently has an effect on the boarding and alighting process. In this paper, two typical control methods are investigated: the schedule-based and headway-based holding control strategies. Schedule recovery is only triggered by schedule deviation independent of control strategies. Such time deviation can be readily informed to drivers. The driver adjustment is related to the schedule adherence status of the bus. In what follows, the corresponding schedule deviations are identified and the effect of schedule recovery are incorporated.

2.3.1. Schedule-Based Holding Control (SH). Under SH, buses either depart on schedule or immediately after serving passengers if they arrive late at the time point [2]. Therefore, the scheduled departure time takes the following piecewise function:

$$d_{i,j} = \begin{cases} s_{i,j}, & a_{i,j} < s_{i,j} - D_{i,j} \\ a_{i,j} + D_{i,j}, & a_{i,j} \ge s_{i,j} - D_{i,j} \end{cases} \quad (12)$$

where $s_{i,j} - D_{i,j}$ is the critical arrival time after which the bus has to depart later than the scheduled departure time $s_{i,j}$.

The scheduled departure time at a designated stop $s_{i,j}$ can be calculated as the scheduled departure time from the previous stop $s_{i,j-1}$ plus the scheduled link travel time. The dwell time is included in the scheduled link travel time. The reliability of bus operation under SH depends on the scheduled link travel time. The scheduled link travel time could be set as the average link travel time multiplied by a safety factor (we term it *slack ratio*) to provide time redundancy and thereby absorbs travel time randomness.

When $a_{i,j} < s_{i,j} - D_{i,j}$, the early arriving bus will be held until time $s_{i,j}$. The schedule deviation, and therefore schedule recovery, arises when the bus arrives at a designated stop later than the critical arrival time, i.e., when $a_{i,j} \geq s_{i,j} - D_{i,j}$, then the delay experienced by bus i at stop j is $d_{i,j} - s_{i,j}$. Similar to Chen et al. [22] and Yan et al. [25], the driver's adjustment between the current time point and the preceding time point is assumed to be proportional to the schedule deviation at the current point. Therefore, the driver adjustment can be estimated as $\beta_{i,j}(d_{i,j} - s_{i,j})$. As a result, by modifying (1), the arrival time with schedule recovery is

$$a_{i,j+1} = d_{i,j} + t_{i,j} - \beta_{i,j}\left(d_{i,j} - s_{i,j}\right) \tag{13}$$

where $\beta_{i,j}$ represents the adjustment factor between stop j and $j+1$ for bus i. In practice, this adjustment parameter can be estimated from historical trip information and is a stochastic variable following a specific distribution will be discussed in Section 2.3.3.

2.3.2. Headway-Based Holding Control (HH). HH approach is usually triggered by headway deviation. In line with SH control, schedule recovery in HH works when arrival delay arises. In this study, we use a heuristic HH similar to that proposed by Sánchez-Martínez et al. [13]. The rational is that hold bus i at control point j to ensure preceding headways are never less than a prescribed design headway. In order to attain the desired headway, when the current headway is smaller than the desired headway, the vehicle should be held at the stop; otherwise, the schedule recovery should be employed. The recovery time is based on the headway deviation. The scenarios are specified as follows.

Scenario I. When the headway is shorter than the design headway, i.e., $h_{i,j} \leq H$, hold bus i at stop j for time $H - h_{i,j}$, thus the arrival at the next stop is simply expressed as

$$a_{i,j+1} = \overline{d}_{i,j} + t_{i,j} \tag{14}$$

Scenario II. When the headway is larger than the design headway, i.e., $h_{i,j} > H$, the bus should depart immediately and schedule recovery starts, and the arrival at the next stop is

$$a_{i,j+1} = d_{i,j} + t_{i,j} - \beta_{i,j}\left(h_{i,j} - H\right) \tag{15}$$

where $h_{i,j} - H$ represents the schedule deviation under headway-based holding control, which can be informed to the bus driver for schedule recovery instruction immediately when bus i completes serving passengers at stop j.

2.3.3. Calibration of Schedule Recovery Factor. As discussed, bus drivers tend to actively pursue schedule recovery if the bus is delayed. Naturally, driver's behavior is highly dependent on the his/her experience, which may vary considerably from scenario to scenario, fleet to fleet, or even from vehicle to vehicle. Therefore, it is reasonable to assume that the schedule recovery factor follows a specific distribution. Based on automatic vehicle location (AVL), automatic passenger counting (APC) data, and the timetable, the delay at stops could be calculated and then correlated with the travel time deviation on the next leg of the journey to the next downstream stop. Consequently, using the historical trip data, one can get the distribution of the adjustment factor $\beta_{i,j}$ along the route.

According to the empirical study by Chen et al. [22], the average adjustment factors vary within a range between -0.5 and 0.5 on most segments. Since the early arrival will be compensated by holding control, here we assume the adjustment factor is nonnegative; that is, bus drivers are always trying to recover the schedule deviation at the preceding time control point.

2.4. Solution Algorithms for Bus Trajectories Evolution. Instead of using simulation tools such as multiagent approach or discrete event-based simulation software (e.g., [33]), in this study we develop bus propagation models to simulate the evolution of bus motion and evaluate the bus holding methods. Unlike the disaggregated models in which system dynamics are explicitly simulated by individual travel behavior, in our simulation framework the passengers' activity is modelled in an aggregated way. The advantage of aggregate models is their greater computational efficiency, which facilitates repeated simulation.

With the above formulations, Algorithm 1 outlines the general simulation framework in which alighting process, capacity constraint, and leftover passengers are incorporated. The algorithm is made up of three components: calculating, respectively, the departures of buses, link travel times, and dwell times. We consider a unidirectional bus route where vehicles depart from one terminal to another. Although extension from one-way line to the general bus route with bidirectional traffic would be straightforward, the modelling a unidirectional route avoids considering traffic continuity at terminal stations and fleet size limitation problem as with the cyclic route where inbound and outbound headways are correlated. Since late or early arrivals at terminals can occur due to travel time variability [34], modelling cyclic route may also result in departure headway fluctuations from the terminals. Such effect is a special case of travel time variability. Let M denote the fleet size of the modelled bus line and N the number of bus stops on the corridor served by the bus line. To discourage bunching at the beginning of the simulation, headways are set deterministic and at a uniform headway; thereafter headways become stochastic. In order to make the system evolve to be chaotic enough for bus bunching to appear, the number of buses M is set sufficiently large in each run of simulation. In this regard, one may consider the simulation of the first few buses in the system as a "warm-up" period.

In order to avoid bus overtaking phenomenon, the bus headway $h_{i,j}$ is required to be larger than a value. When the preceding bus is caught by the next incoming bus during the

Initialization: Set input parameters and the counter of simulations
Procedure:
Step 1: Generate the departure times for all trips from the terminal
for bus i=1: M **do**
  Compute the departure time for the bus line, satisfying $d_{i,1} := d_{1,1} + (i-1)H$
end
Step 2: Generate the stochastic bus link travel time
for bus i=1: M **do**
  for stop j=2: N **do**
    Compute the bus link travel time $t_{i,j-1}$ from a truncated normal distribution.
  end
end
Step 3: Generate the full trajectories of the first bus
for stop j=2: N **do**
  Compute the arrival time of bus 1 at stop j, satisfying $a_{1,j} := d_{1,j-1} + t_{1,j-1}$
  Compute the departure time of bus 1 from stop j, satisfying $d_{1,j} := a_{1,j} + P(q_j H)/b$
  Compute the number of on-board passengers, satisfying $L_{1,j} := L_{1,j-1}(1-\rho_j) + P(q_j H)$
    Let the leftover demand, $l_{1,j} := 0$
end
Step 4: Generate the trajectories for the remaining trips of the bus line
for stop j=2: N **do**
  for bus i=2: M **do**
    Compute the trajectory and passenger flows of bus i at stop j using Eqs.(1)-(11) subject to Eqs.(16)
    Apply holding control and schedule recovery where necessary, and update the departure time according to Eqs.(12)-(15).
  end
end

Algorithm 1: Bus trajectories evolution algorithm.

simulation, i.e.,$h_{i,j} < 0$, let the preceding bus restart after a delay time δ, which we call it *minimum safety interval*, i.e.,

$$a_{i,j} = \overline{d}_{i-1,j} + \delta \tag{16}$$

3. Performance Measure

To evaluate the performance of different control strategies, we use a number of performance measures to take into account the views of different stakeholders: passengers and operator. The headway variability is the major concern of both passengers and operator, since uneven headway is the main cause of spatially uneven loads and thus bus bunching. The average waiting time reflects the level of service and appears to be uppermost for passengers. In addition, the operator may concern the travel time reliability, since it is crucial for schedule design and operation costs. A smoother and more robust operation and planning at terminals requires lower variability of travel time. Multiple simulation runs are conducted, from which we generate distributions of performance measures.

3.1. Headway Variability Coefficient (HVC). Similar to Turnquist and Bowman [35], Liu and Sinha [36], and Wu et al. [37], we use the headway variability coefficient (HVC) to measure the reliability of the observed headways, which is defined as the ratio of the standard deviation to the mean headway. This coefficient is the coefficient of variation as known in statistics and probabilities.

3.2. Average Waiting Time. As mentioned previously, in this study, the passengers' activity is modelled in an aggregated way; thus it would be difficult to obtain the waiting time of each individual passenger. The average passenger waiting time could be achieved by (6)-(8).

The waiting passengers at a station are divided into two groups: those who are able to board and those who are left behind due to capacity constraint. The former, of which the number is $\overline{B}'_{i,j}$ (see (7)), arrives randomly during time window $[0, h_{i,j}]$; thus their expected waiting time can be approximated to be half of the headway $h_{i,j}/2$ (Sánchez-Martínez et al. [13]; Salek and Machemehl [30]). The passengers who are left behind, $l_{i-1,j}$, have to wait for the next bus, and their additional waiting time is the entire headway$h_{i,j}$. Summing up these two groups we have the total waiting time expressed as $(1/2)\sum_i\sum_j \overline{B}'_{i,j}h_{i,j} + \sum_i\sum_j l_{i-1,j}h_{i,j}$.

Dividing the total waiting time by the total number of boarding passengers $\overline{B}_{i,j}$(see (6)), we have the average waiting time per passenger as follows:

$$\begin{aligned}\overline{w} &= \frac{(1/2)\sum_i\sum_j \overline{B}'_{i,j}h_{i,j} + \sum_i\sum_j l_{i-1,j}h_{i,j}}{\sum_i\sum_j \overline{B}_{i,j}} \\ &= \frac{\sum_i\sum_j \left(\overline{B}'_{i,j} + 2l_{i-1,j}\right)h_{i,j}}{2\sum_i\sum_j \overline{B}_{i,j}}\end{aligned} \tag{17}$$

As shown in Section 2.2, the number of waiting passengers and the headways are interdependent. The expected

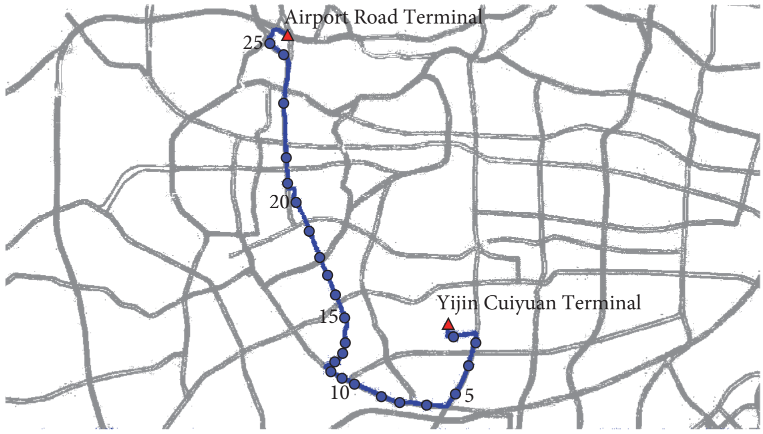

Figure 2: Bus route 87. The direction of the bus route discussed in this article is from the bottom to the up.

average waiting time $E(\overline{w})$ can be drawn from multiple simulation runs.

3.3. Average Travel Time. While bus holding control could improve the service regularity, it prolongs the terminal-to-terminal running time for the vehicles. The average travel time for buses is an important operational performance measure for transit operators since it is related to the fleet size. In each run of simulation, an average travel time is derived as the arithmetic mean over all buses simulated. Then an expected average travel time, derived from multiple simulation runs, is used as the performance measure.

3.4. Load Variation. Headway variability and bus bunching lead to uneven load. Such spatially heterogeneous demand is one of the major sources triggering crowding effect since discomfort happens at high load factors. Therefore, a more balanced load factor across buses yields a more comfortable experience to users. In view of this, we introduce load variation to evaluate the performance of bus control strategies, which is defined as the standard deviation of all bus loads across all segments. Then the expected load variation can also be drawn from multiple simulation runs.

4. Comparative Results on a Simulated Real-Life Route

In this section, we compare the performance of two bus holding controls with and without schedule recovery (SR) effort: the simple schedule-based holding (SH) and headway-based holding (HH) and SH with schedule recovery (SHSR) and HH with schedule recovery (HHSR).

These four control methods are applied to bus route 87 in the city of Guangzhou, China. The bus route (shown in Figure 2) has a total distance of 14.7 km. It connects Yijin Cuiyuan Terminal and Airport Road Terminal in the city. The passenger demand and link travel time data are provided by a local bus company. We use the data during the morning peak hour (9:00-10:00 am) and in the direction from Yijin Cuiyuan Terminal to Airport Road Terminal in the city. The scheduled headway of the route is taken as 8 minutes.

Following Liu et al. [32], we assume that passengers boarding at a station will evenly alight at the downstream stops; thus the stop-specific average alighting rate ρ_j can be obtained from the boarding rate. Table 1 shows the empirical data on passenger arrival rate and the derived alighting distributions. The link travel time data are obtained from on-board GPS tracking devices, from which the mean and standard deviation of travel time between stops are calculated and listed in Table 2. At present, the bus route operates in an unscheduled and uncontrolled manner.

The minimum safety interval is set as $\delta = 0.3\ min$, the average boarding and alighting time are set as $\alpha = 2s$ and $b = 4s$, respectively, and vehicle capacity is set as $C = 100\ pax/veh$. The open and close door time is taken as $\tau = 4s$. The threshold of the in-vehicle crowding degree φ is set to be 0.8. The crowding coefficient is set as $\gamma = 1.5$, and the number of buses M is set as 20. In order to highlight the relative effect of holding and schedule recovery, all intermediate stops are considered key time control stops. Buses are set to depart from the terminal on time in the base case. The link riding times are drawn from a truncated normal distribution with means and standard deviations as listed in Table 2. The simulation is run 1000 times.

The detailed output in a typical simulation includes vehicle trajectories, the vehicle load, and the number of leftover passengers. In what follows, we test the effectiveness of the simulation model under various operating settings. To represent differences in driver behavior and their impact on schedule recovery, in each simulation the schedule recovery factor β_{ij} is randomly generated for each segment following a uniform distribution.

4.1. Slack Ratio for Schedule-Based Holding Control. The slack time is a crucial predetermined setting for SH control. To investigate, we define slack ratio as the multiplier of average link travel times, and we test the system performance for a range of slack ratios: $\{0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.5\}$.

Table 1: Observed passenger arrival flow and derived alighting proportion on 87 Route.

stop	1	2	3	4	5	6	7	8	9	10	11	12	13
Arrival rate (pax/min)	0.34	0.22	0.17	0.23	0.25	0.27	0.45	0.91	0.64	0.99	0.56	0.74	0.25
Alighting Proportion (%)	0	4.2	4.3	4.5	4.8	5	5.3	5.6	5.9	6.3	6.7	7.1	7.7
Stop	14	15	16	17	18	19	20	21	22	23	24	25	
Arrival rate (pax/min)	0.79	0.26	0.38	0.35	0.27	0.29	0.30	0.11	0.14	0.08	0.06	0.03	
AlightingProportion(%)	8.3	9.1	10	11.1	12.5	14.3	16.7	20	25	33.3	50	100	

Table 2: Observed mean and standard deviation of link travel times on 87 Route (unit: min).

stop	1	2	3	4	5	6	7	8	9	10	11	12	13
Mean	1.46	2.05	0.89	1.87	1.66	1.65	1.63	4.41	0.82	0.79	0.83	1.35	0.2
STD	2	0.7	1.6	0.47	0.27	0.68	0.63	2.63	0.51	0.23	0.26	0.67	0.03
Stop	14	15	16	17	18	19	20	21	22	23	24	25	
Mean	3.27	2.72	3.04	2.90	1.53	2.21	2.94	1	2.64	2.56	0.74	1.6	
STD	1.07	0.75	1.22	1.36	0.48	1.03	1.06	0.28	0.73	0.66	0.27	0.28	

Moreover, for a given slack ratio, we introduce two levels of schedule recovery effort: a low level uniformly distributed in an interval [0.1, 0.2] and a high level in an interval [0.4, 0.5]. The results are shown in Figure 3. A summary of findings and their implications is listed as follows.

(a) In aspect of HVC, the HH control generally outperforms the SH under various slack ratios (Figure 3(a)). However, in the provision of schedule recovery, the HH is not always better than SH control in passenger waiting time $E(\overline{w})$, when the slack ratio lies between 0.6 and 1.2 (Figure 3(b)). The average travel time under HH control is shorter than that of SH when the slack ratio is larger than 2 (Figure 3(c)). When the slack ratio ranges from 0.6 to 1.2, the SH with high level of schedule recovery presents the less variability and most uniform pattern in bus loads (Figure 3(d)).

(b) The load variation (Figure 3(d)) under SH first decreases and then increases with the increasing slack ratio. There are two possible reasons for this. First, 1.2 is already a high slack ratio to mitigate travel time variability; any improvement of headway stability could become more difficult through increasing the slacks. Second, higher slacks lead to less frequent service and greater accumulated boarding demand, which could in turn result in high crowding at some stops.

(c) Performance improvements for all indicators are observed at more sophisticated holding strategies with SR. The improvement is more significant when more schedule recovery effect is made. This is because schedule recovery compensates holding times vehicle spending. For SH control, schedule recovery could improve performance by a greater degree when the slack ratio is smaller. The reason is that when the slack time is sufficiently large, most of the travel time randomness and resulting delay have been mitigated, such that schedule recovery takes less effect. Therefore, one can see that when the slack ratio is relatively small, the benefit of HVC, waiting time, and travel time gained by schedule recovery is greater with SH control.

Naturally, a longer slack time for SH will lead to better schedule adherence, but at an expense of the negative effect of less frequent service and greater mean headways. As shown in Figure 3(b), such negative effect would overweight the reduction of headway variation when the slack time reaches a threshold (about 1); thereafter the waiting time increases instead. This suggests that sufficient holding times is not productive, and the operator should make a trade-off between the headway stability and efficiency in the planning. Hence, we analyse in the following the performance of holding control strategies with a reasonable level of slack ratio, at 1. Optimizing the slack time has been left for future study. In addition, to highlight the effect of schedule recovery effort, from now on the schedule recovery factor is set as a high level, i.e., uniformly distributed in an interval [0.4, 0.5]. The control policies are compared under the same operational settings, except where they are the subject of a test. This is approximated in the interest of presenting the incremental improvement, though it might be possible to improve performance further by optimizing headway.

4.2. Sensitivity to Travel Time Variability. In this section, we analyse the performance improvement from schedule recovery under various levels of travel time variability. The performance improvement is calculated as relative performances between with and without SR controls: $(SH-SHSR)\times 100/SHSR$ or $(HH - HHSR) \times 100/HHSR$. The travel time variability is reflected by the standard deviation of truncated normal distributed link travel time. We amplify the standard deviation by factors 1.2, 1.4, 1.6, 1.8, and 2. The results are presented in Figure 4.

When the travel time variability increases, more performance improvement could be achieved by schedule recovery. While schedule recovery benefits both of the holding control strategies, the performance improvement of SHSR is much greater than that of HHSR under the same level of travel time variability. Since schedule recovery acts as the contributor to service recovery, these results suggest that SH is more sensitive to schedule recovery than HH in the presence of the travel time variability. In other words, SH method is less able to stabilize headways but could benefit more from schedule

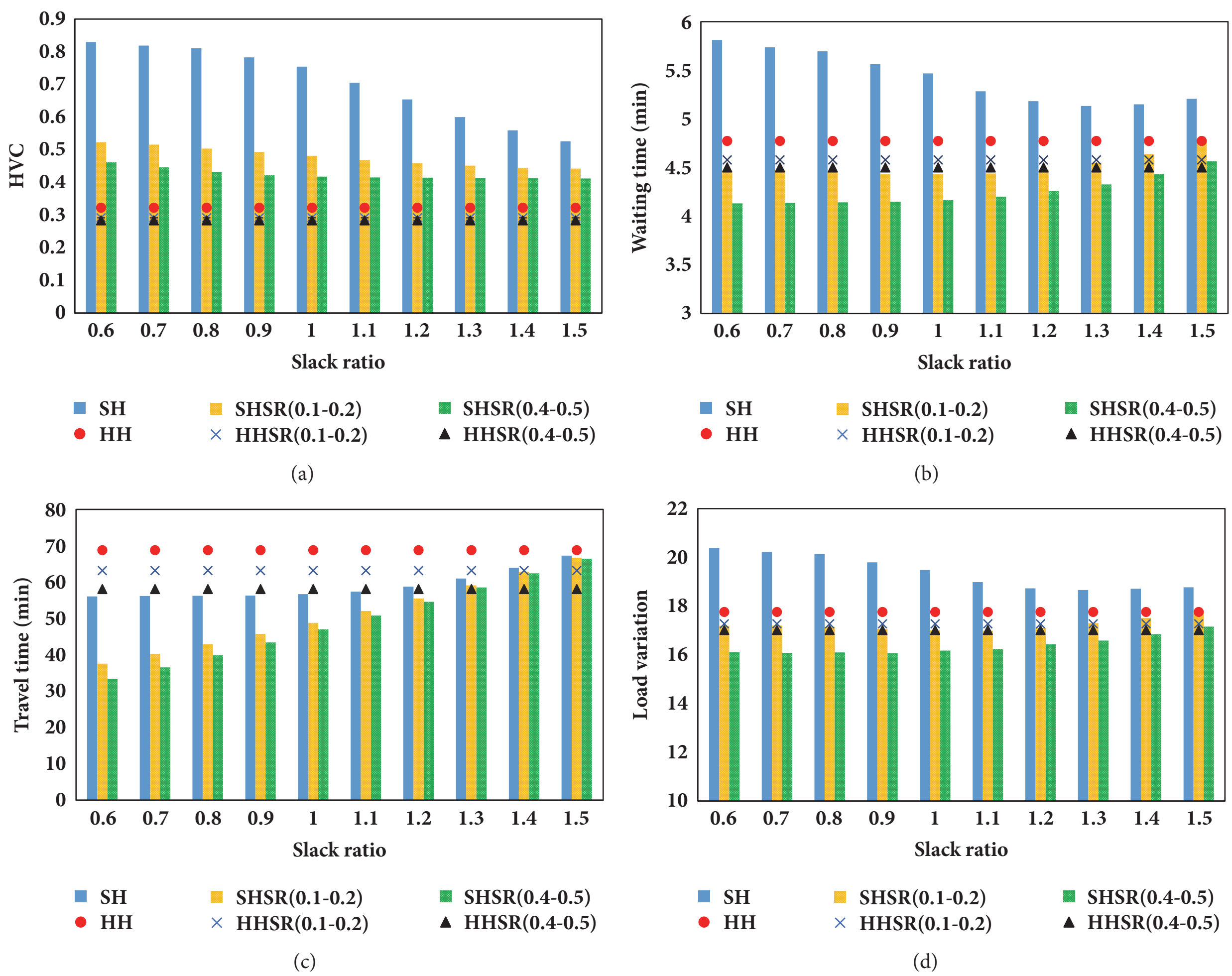

FIGURE 3: Performance measures under different control policies: (a) HVC; (b) $E(\overline{w})$; (c) average travel time; (d) load variation.

recovery. This implies that, in practice, cruising guidance technology has more effect in SH rather than HH under the same schedule recovery effort.

4.3. Sensitivity to Total Demand. Demand is one of the most important factors affecting the performance of the control strategy. To analyse the independent effect of demand congestion on the holding control performance, in this section we vary the demand levels without changing the headway and vehicle capacity. Figure 5 shows performance measures with varying demand levels.

SH appears to take no effect in terms of HVC in high demands (Figure 5(a)). A possible reason is that the effect of SH method is closely related to dwell times; when the demand volume grows (unless exceeding the capacity), buses are likely to stay longer at stops and depart later than the given scheduled departure time. Such effect may propagate along the downstream route. Consequently, the schedule departure times in SH takes less effect as the demand volume grows. This suggests that operators should pay attention to the level of passenger demand when using SH method.

HH is more sensitive to demand variation than SH in terms of average waiting time (Figure 5(b)). HH works well only in low demand; when the demand increases, the control performance deteriorates quickly in the average waiting time. In particular, SH outperforms HH in terms of the average waiting time when the demand ratio is larger than 2. This is because, as discussed previously, SH takes less effect with higher demand, whereas HH is always in effect regardless of the demand level. In this sense, the service frequency under HH will be reduced as the demand increases as opposed to SH.

Bus load variation for both SH and HH increases with the demand ratio but at a decreasing rate (Figure 5(d)). This is because when the demand level reaches a threshold, the bus capacity can only meet the transport demand of the first several bus stops, after which buses tend to be full of passengers at the following stops. Schedule recovery takes more effect in smoothing bus loads under SH compared to HH. As the demand ratio reaches 2, the effect of schedule recovery is trivial for HH.

4.4. Summary of the Key Findings and Their Practical Implications. In this section, we highlight the key findings from the sensitivity analysis of the proposed holding control with schedule recovery and discuss their operational implications.

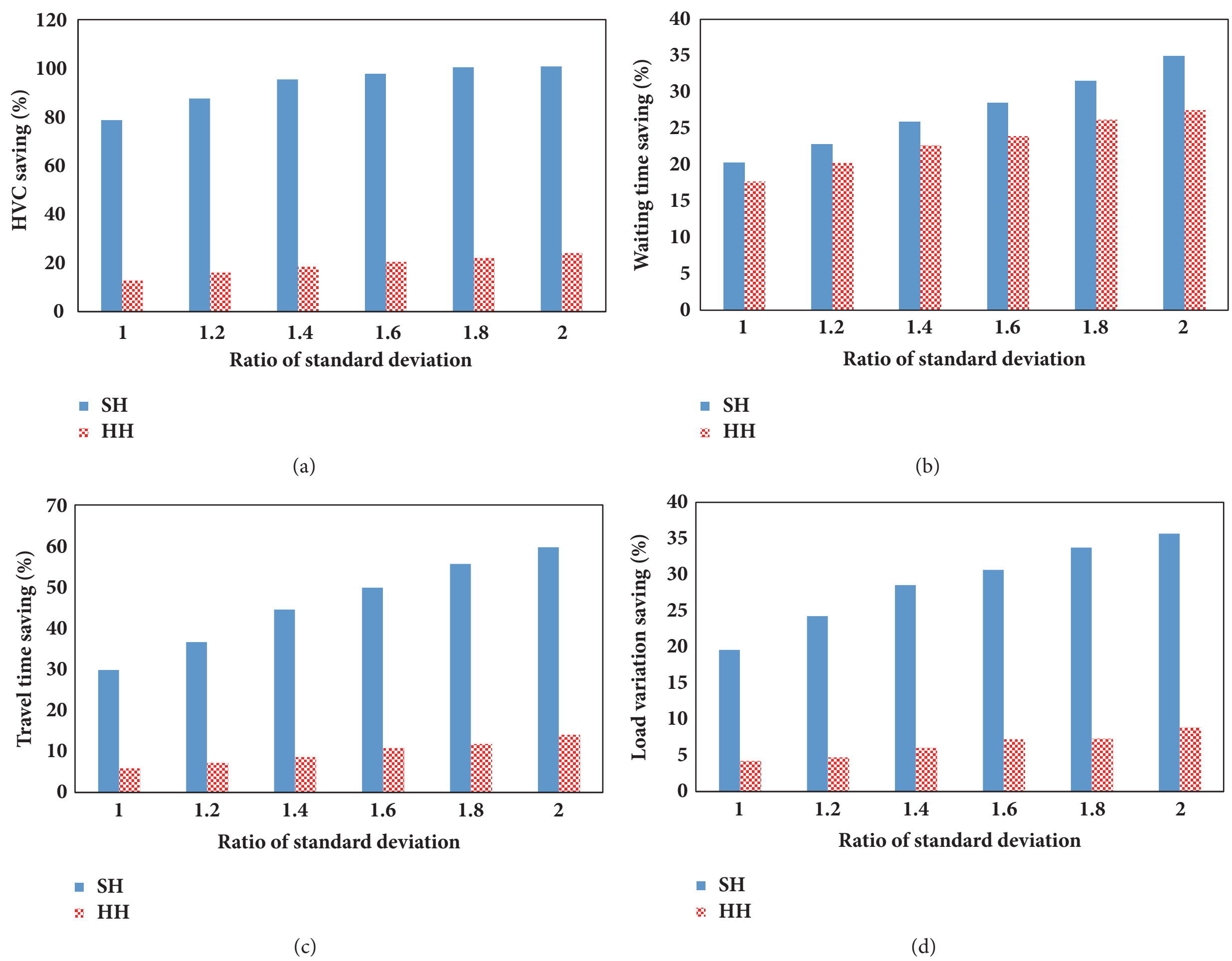

Figure 4: Percentage reductions in (a) HVC; (b) $E(\overline{w})$; (c) average travel time; (d) load variation under different travel time variation levels.

First, HH method generally outperforms the SH method with respect to HVC (Figure 3(a)). When schedule recovery (SR) effort is included; however, the relative performance of HHSR and SHSR would depend on the slack time. HHSR outperforms SHSR only with large slack ratios.

Second, we have shown that bus performance will always improve with SR effort, and SH control benefits more than HH control with SR, particularly in the presence of travel time variability (Figure 4). SR has less effect with larger slack ratios (Figure 3), and its effect in smoothing bus loads is greater under SH than under HH (Figure 5(d)).

Third, due to the inherent control mechanism, the SH takes less effect as the demand grows, whereas HH is always in effect. This may result in the phenomenon that SH outperforms HH in aspect of waiting time when the demand is sufficiently high (Figure 5(b)).

Based on the key findings described above, the following practical insights and recommendations can be drawn.

(a) *Bus Stop Layout (Re)design*. The above results show that cruising guidance and schedule recovery could improve the reliability of bus system. To facilitate the en route driver guidance and schedule recovery effort, some strategies can be introduced. For example, fewer stop activities and passenger flow control should be encouraged. According to the previous empirical analysis, bus stop consolidation has no significant effects on passenger activity [38]. Therefore, transit planners should make a trade-off between stop spacing and passengers' access to service in the design or redesign of bus route and possibly introduce wider stop spacing through the removal or consolidation of existing stops. Since the bus service time at bus stop areas usually occupies a large proportion of the total on-road bus operational time, it would also be helpful to invest in a quicker fare collection technology, such as building enclosed areas to allow off-bus fare collection for rapid boarding like the bus rapid transit system. In addition, for those bus routes traversing the center and suburb, such as Express Route 2 of Suzhou City in China, the stops in the suburban area with low demand could be converted into request stops (or flag stops), at which the vehicle will stop only on request.

(b) *Determination of Slack Times*. Including slack times in the schedule could stabilize headways, whereas too much slacks reduce service frequency. Transit operator need to consider the trade-off between the headway stability and efficiency in the planning. In the presence of schedule recovery, schedule-based method could achieve the best compromise

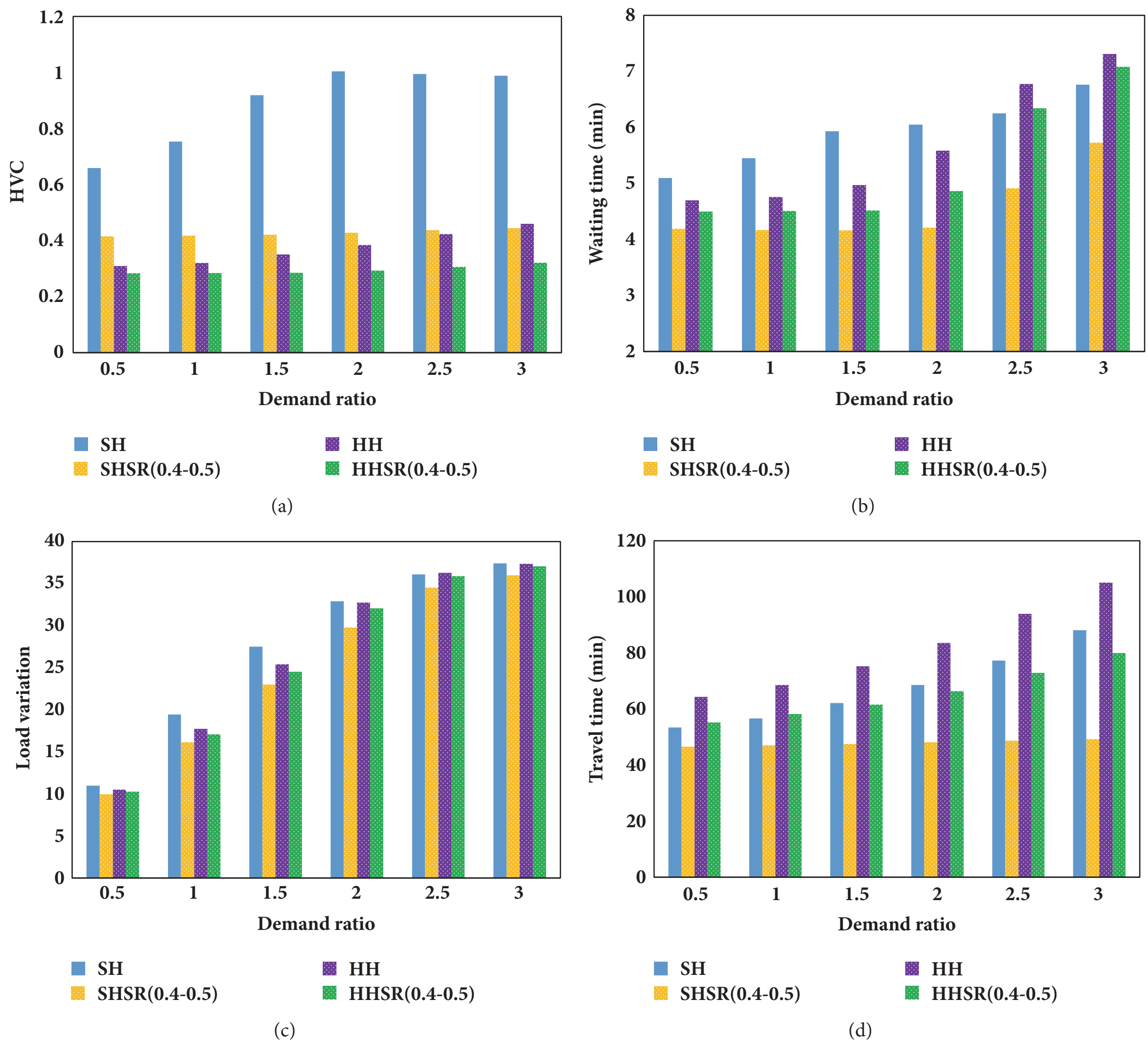

Figure 5: Performance measures for different total demand: (a) HVC; (b) $E(\overline{w})$; (c) average travel time; (d) load variation.

between headway regularity and efficiency with reasonable amounts of slack times, making it the preferable method for routes to reduce the waiting time.

(c) *Selection of Bus Holding Control Method*. Simulation results show that SH could benefit more from schedule recovery compared to HH under the same level of schedule recovery effort. Such property can be utilized to choose proper tactics in response to different operational conditions. Since there exist potential safety issues for schedule recovery, such as speeding and pushing traffic lights when there is little time left for the driver to catch up with the arrival schedule, the SH is preferable in the case of dedicated bus lanes, exclusive right of ways, or wide stop spacing where cruising guidance and schedule recovery could be more easily implemented. On the other hand, the HH may be recommended when the cruising guidance technology is absent or restricted, such as in normal lanes exposed to exogenous conditions. This is also the case during peak hours and traffic congestion, which implies that HH might be converted to SH in the transitional period from peak to off-peak hours, vice versa. Therefore, in practice, transit agencies should be mindful of choosing bus control methods in the context of cruising guidance technology. In addition, since SH will take less effect with higher demand as opposed to HH, transit operators should pay attention to the level of passenger demand when choosing control method.

5. Concluding Remarks

This study was conducted to understand the impact of schedule recovery on real-time holding control strategies for a fixed bus route. Such schedule recovery behavior is readily available in the context of cruising guidance technology but so far has been neglected in the holding control analysis and evaluation.

To capture the stochastic nature of travel times and demand, we first developed a bus propagation model with vehicle capacity constraint, which was extended by combining with the real-time holding control strategies (i.e., schedule-based and headway-based) and the effect of schedule recovery. The recovery time is proportional to the arriving delay time and the corresponding adjustment factor. Such stop-specific factor could be calibrated with the help of AVL-APC data.

The combined effects of holding control and schedule recovery were tested through a case study for a simulated real-life bus route in Guangzhou, China. We analysed and compared how the schedule recovery behavior affects the system performance of two holding control methods under different operating settings. We found that schedule recovery acts as the contributor to service reliability, and that schedule-based holding method is less able to stabilize headways but could benefit more from schedule recovery compared to headway-based holding method. The findings are specific to a real-life simulated bus route. The comparative results can help provide supporting tool for different bus control options and bus stop design in the provision of emerging technologies.

Future research may continue to develop an extended list of operational tactics and compare the combined effects under various operational settings. There exist common-line corridors where several bus lines serve the same stops [39]. The further study will also extend to considering multiple bus lines and investigate the impact of common-line stops on the system performance.

Notations

i: The subscript of vehicle
j: The subscript of bus stop
C: The vehicle capacity
q_j: The passenger arrival rate at stop j (pax/min)
ρ_j: The alighting proportion at stop j (%)
b: The average boarding time for passengers (s)
α: The average alighting time for passengers (s)
H: The design headway of a bus line (min)
$\beta_{i,j}$: The adjustment factor between stop j and $j+1$ for bus i
δ: Minimum safety interval (min)
$h_{i,j}$: The headway between bus i and the preceding bus at stop j (min)
$a_{i,j}$: The arrival time of bus i at stop j (min)
$d_{i,j}$: The departure time of bus i at stop j (min)
$t_{i,j}$: The travel time between stop j and $j+1$ for bus i (min)
$B_{i,j}$: The total number of waiting passengers for bus i at stop j during the headway (pax)
$\overline{B}_{i,j}$: The actual number of boarding passengers for bus i at stop j during the headway (pax)
$\overline{B}'_{i,j}$: The actual number of arriving passengers at stop j who are able to board bus i during the headway (pax)
$A_{i,j}$: The number of alighting passengers of bus i at stop j (pax)
$D_{i,j}$: The dwell time for bus i at stop j (min)
$s_{i,j}$: The scheduled departure time of bus i at stop j for schedule-based holding control (min)
$l_{i,j}$: The number of leftover passengers of bus i when it departs from stop j (pax)
$L_{i,j}$: The number of on-board passengers of bus i between stop j and $j+1$ (pax).

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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