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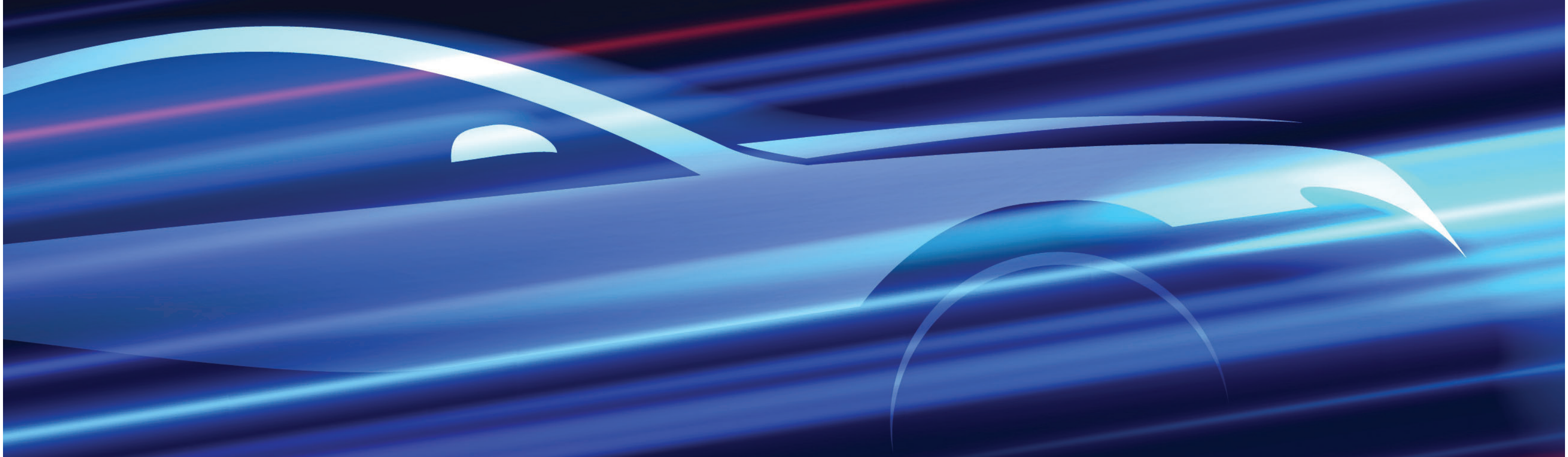

MONOGRAPH

MODERN MOBILITY: CHALLENGES AND DEVELOPMENT TRENDS

Smart cities
and future mobility

PRIORITY RESEARCH AREAS SILESIAN UNIVERSITY OF TECHNOLOGY

Silesian University of Technology

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

WYDAWNICTWO POLITECHNIKI ŚLĄSKIEJ
GLIWICE 2023
UIW 48600

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ISBN 978-83-7880-950-0

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SPIS TREŚCI

INTRODUCTION

The publication is the next volume of the series on smart cities and future mobility, related to Priority Research Area 4 (POB4).

The research and the analysis carried out at the Silesian University of Technology indicate possibilities how science can be useful at sustainable development on a local, regional and global scale.

Modern mobility is characterized by the need to overcome many development barriers. The publication discusses selected of them, including the problem of accessibility of public collective transport in terms of space and time, shaping a safe and intelligent transport infrastructure, as well as the problem of the development of electromobility. The second part of the study includes issues related to the construction and modernization of vehicle structures.

We would like to thank the sub-area coordinators in POB4 for their significant contribution to the creation of this volume, the authors of all chapters for presenting the results of research and analysis, and the reviewers for their valuable comments.

Giving this publication to the Readers, we trust that you will find an interesting area to establish cooperation or its further development with the Silesian University of Technology.

Małgorzata Król, Piotr Krauze and Grzegorz Sierpiński

Gliwice, 2023

DOI:10.34918/87421

Jacek WIDUCH[1]

1. MODERN VARIANTS OF VEHICLE ROUTING PROBLEMS

1.1. Introduction

The Vehicle Routing is a subject of research for more than 50 years when it was formulated by Dantzig and Ramser as an example of problem delivering gasoline to service stations[2]. It belongs to the group of optimization problems concerned with the determination of routes for the given fleet of vehicles which serve a set of customers satisfying defined constraints and objectives. It is realized in practice every day by thousands of companies over the world engaged in the delivery of different types of goods. It is used in areas influencing the modern economy and the cost of goods, such as logistics, communication, transport, manufacturing, civil and military systems. Over the years, the models and variants of the VRP have changed to reflect reality as accurately as possible.

This chapter focuses on some of the most popular contemporary research problems related to determining routes of vehicles. In recent years, new variants of delivery vehicles have been considered. The vast majority of vehicles run on combustion engines. Electrically powered vehicles are becoming more and more popular. New problems are associated with the use of electric vehicles, such as the availability of charging stations, longer charging time than refueling traditional combustion vehicles, shorter range. When designating travel routes and selecting the types of vehicles used, their impact on the surrounding environment and the generated pollution are more and more often taken into account. Ecological issues have become an important factor in transport planning. Another variant of the increasingly popular vehicles are unmanned vehicles.

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[1] Silesian University of Technology, Faculty of Automatic Control, Electronics and Computer Science, Department of Algorithmics and Software, Gliwice, e-mail:jacek.widuch@polsl.pl.

[2] Dantzig G.B., Ramser J.H.: The truck dispatching problem, Management Science, 1959, Vol. 6, pp. 80–91.

The structure of this chapter is as follows. Section 2 presents the classical Vehicle Routing Problem (VRP). In subsection 2.1 the problem definition is presented and subsection 2.2 presents mathematical model. Section 3 presents selected modification of the VRP. In section 4 Green Vehicle Routing Problem is presented. Section 5 presents Electric Vehicle Routing Problem. In section 6 Unmanned Vehicle Routing Problem is presented. Finally, section 7 contains concluding remarks.

1.2. The classical vehicle routing problem

1.2.1. The problem definition

The classical Vehicle Routing Problem (VRP) is also known as Capacitated Vehicle Routing Problem (CVRP) and it was defined in 1959 by Dantzig and Ramser[3]. The VRP can be considered as combinatorial problem and it can be described as follows. Let $G = (V, A)$ be a weighted graph with the weight function $d : A \rightarrow R_{\geq 0}$. The graph G contains a set of vertices $V = \{0, 1, \ldots, n\}$, where vertex 0 represents the depot and vertices $1, \ldots, n$ represent customers to be served. Each customer i ($i = 1, \ldots, n$) is characterized by a demand $q_i \geq 0$, the depot 0 has a demand $q_0 = 0$. The set $A = \{(i, i) : i, j \in V\}$ is the set of arcs linking vertices i and j with a weight d_{ij} which can be interpreted as a distance from i to j. The set of m vehicles, based at the depot 0, is available to serve customers $1, \ldots, n$ where each vehicle has the same maximum load capacity c (a homogenous fleet of vehicles is considered). The goal of VRP is to determine a set vehicle routes with the least total distance satisfying following conditions:

- each customer $1, \ldots, n$ is visited exactly once by exactly one vehicle,
- each vehicle starts and ends its route at the depot 0,
- the total load of each vehicle does not exceed the maximum load c.

A graphical illustration of the VRP is shown in Fig. 1.1. The number of customers is 14 and the solution contains three routes marked in blue, green and red.

[3] Dantzig G.B., Ramser J.H.: The truck dispatching problem, Management Science, 1959, Vol. 6, pp. 80–91.

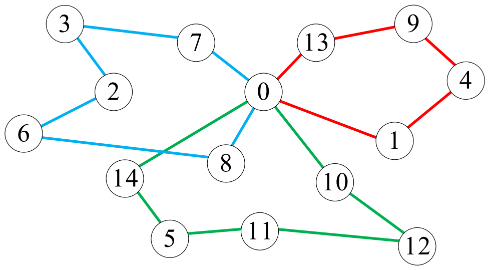

Fig. 1.1. A graphical presentation of the VRP
Rys. 1.1. Graficzna prezentacja problemu trasowania pojazdów

The VRP is an NP-hard problem[4]. Thus, exact solution of large problem is difficult to obtain. A new real-life challenges and practical applications require extensive modifications and new variants of the VRP. Thus the VRP is extended by including additional real-life aspects resulting many variants of the problem.

1.2.2. Mathematical model

Mathematical model of the VRP can be presented as follows[5]. Let x^k_{ij} be a binary decision variable which is equal to 1 only if arc $(i, j) \in A$ belongs to the optimal solution and it belongs to the route served by vehicle k ($k = 1, \ldots, m$) and it is equal to 0 otherwise. The objective of the problem is to minimize the total distance defined as follows:

$$\text{minimize } \sum_{k=1}^{m} \sum_{i \in V} \sum_{j \in V} d_{ij} x_{ij}^{k} \tag{1.1}$$

subject to the following constraints:

$$\sum_{k=1}^{m} \sum_{i \in V} x_{ij}^{k} = 1 \quad (j = 1, \ldots, n) \tag{1.2}$$

$$\sum_{k=1}^{m} \sum_{j \in V} x_{ij}^{k} = 1 \quad (i = 1, \ldots, n) \tag{1.3}$$

$$\sum_{k=1}^{m} \sum_{j \in V} x_{0j} = m \tag{1.4}$$

$$\sum_{k=1}^{m} \sum_{i \in V} x_{0i} = m \tag{1.5}$$

$$\sum_{i \in V} \sum_{j \in V} q_j x_{ij}^{k} = c \quad (k = 1, \ldots, m) \tag{1.6}$$

[4] Lenstra J.K., Rinnooy Kan A.H.G.: Complexity of vehicle and scheduling problems, Networks, 1981, Vol. 11, pp. 221–227.
[5] Borčinová Z.: Two models of the capacitated vehicle routing problem, Croatian Operational Research Review, 2017, Vol. 8, pp. 463–469.
Laporte G.: The vehicle routing problem: An overview of exact and approximate algorithms, European Journal of Operational Research, 1982, Vol. 59, pp. 345–358.

The constraints (1.2) and (1.3) ensure that each customer is visited by exactly one vehicle. The constraints (1.4) and (1.5) guarantee that each vehicle can leave the depot only once and returns to the depot. The constraints (1.6) ensure the capacity constraints are satisfied, i.e. the sum of the demands of the customers visited in a route does not exceed the vehicle capacity c.

1.3. Selected modifications of the classical vehicle routing problem

The VRP model introduced in 1959[6] was extended to incorporate many realistic aspects like time-dependent travel times, time windows for pickup and delivery, input data that changes dynamically over time, multi depots, type of goods transported and type of vehicles, etc. These additional aspects bring along substantial complexity. Selected considered modifications of the VRP are following:

- Vehicle Routing Problem with Time Windows (VRPTW): given is the time windows constraints, i.e. customers opening and closing hours, to ensure that vehicles visit customers within a specific intervals. If vehicle arrives outside time window it waits until opening the window and there is waiting cost[7].
- Open Vehicle Routing Problem (OVRP): the vehicle is not required to return to the depot after visiting customers it can terminate at one of the customers or other points[8].
- Hazardous Vehicle Routing Problem (HVRP): transportation of hazardous materials (HazMat). HazMat include substances, solids or gases that can be flammable, toxic, explosive or radioactive and are the most threatening to the environment and to the human health even if they are transported under rules. There are areas where the transportation of HazMat is forbidden and it must be considered in route planning[9].
- Large-Scale Vehicle Routing Problem (LSVRP): it is related to the scale of the problem instances with more than 200 customers[10].

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[6] Dantzig G.B., Ramser J.H.: The truck dispatching problem, Management Science, 1959, Vol. 6, pp. 80–91.
[7] Villalba A.F.L., La Rotta E.C.G.: Clustering and heuristics algorithm for the vehicle routing problem with time windows, International Journal of Industrial Engineering Computations, 2022, Vol. 13, pp. 165–184.
[8] Dasdemir E., Testik M.C, Öztürk D.T., Sakar C.T., Güleryüz G., Testik Ö.M.: A multi-objective open vehicle routing problem with overbooking: Exact and heuristic solution approaches for an employee transportation problem, Omega, 2022, Vol. 108, pp. 102587.
[9] Ouertani N., Ben-Romdhane H., Krichen S.: A decision support system for the dynamic hazardous materials vehicle routing problem, Operational Research, 2022, Vol. 22, pp. 551–576.
[10] Costa J.G.C., Mei Y., Zhang M.: Adaptive search space through evolutionary hyper-heuristics for the large-scale vehicle routing problem, 2020 IEEE Symposium Series on Computational Intelligence (SSCI), 2020, pp. 2415–2422.

- Vehicle Routing Problem with Stochastic Demands (VRPSD): the problem where customer demands are defined by stochastic variables[11].
- Heterogeneous Vehicle Routing Problem (HVRP): the customers are served by heterogeneous fleet of vehicles. The vehicles differ in their capacity and cost per day for using them[12].
- Time Dependent Vehicle Routing Problem (VRP): the travel time is not constant and it is a function of the congestion at peak hours and weather changes[13].
- Vehicle Routing Problem with Simultaneous Delivery and Pickup (VRPSDP): the goods need to be picked up from a customer and must be served to the other customers[14].
- Vehicle Routing Problem with Backhauls (VRPB): modification of VRPSDP, in the each route all deliveries must be made before any pickups of the goods[15].
- Multi Compartment Vehicle Routing Problem (MCVRP): a variant of the problem in which several product types must be transported separately and the vehicle capacity is split or can be split into several zones. It considers the transportation of dangerous goods, liquid or bulk products and the transportation of food products in different temperature zones[16].
- Dynamic Vehicle Routing Problem (DVRP): the input data is revealed or updated continuously. The customers that have been already visited are removed from the network and the customers that placed a new order are added to the network. These changes are used to update routes[17].
- Split Delivery Vehicle Routing Problem (SDVRP): the customer can be visited more than once by the vehicles [18].

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[11] Omori R., Shiina T.: Solution algorithm for the vehicle routing problem with stochastic demands, 2020 Joint 11th International Conference on Soft Computing and Intelligent Systems and 21st International Symposium on Advanced Intelligent Systems (SCIS-ISIS), 2020, pp. 1–6.
[12] Dang Y., Allen T.T., Singh M.: A heterogeneous vehicle routing problem with common carriers and time regulations: Mathematical formulation and a two-color ant colony search, Computers & Industrial Engineering, 2022, Vol. 168, pp. 108036.
[13] Ke-Wei J., San-Yang L., Xiao-Jun S.: A hybrid algorithm for time-dependent vehicle routing problem with soft time windows and stochastic factors, Engineering Applications of Artificial Intelligence, 2022, Vol. 109, pp. 104606.
[14] Ning T., Wang J., Han Y.: Logistics distribution de-carbonization pathways and effect in China: a systematic analysis using VRPSDP model, International Journal of Low-Carbon Technologies, 2021, Vol. 16, pp. 1404-1411.
[15] Subramanian A., Queiroga E.: Solution strategies for the vehicle routing problem with backhauls, Optimization Letters, 2020, Vol. 14, pp. 2429–2441.
[16] Heßler K.: Exact algorithms for the multi-compartment vehicle routing problem with flexible compartment sizes, European Journal of Operational Research, 2021, Vol. 294, pp. 188–205.
[17] Bonilha I.S., Mavrovouniotis M., Müller F.M., Ellinas G., Polycarpou M.: Ant Colony optimization with heuristic repair for the dynamic vehicle routing problem, 2020 IEEE Symposium Series on Computational Intelligence (SSCI), 2020, pp. 313–320.
[18] Ji B., Zhou S., Yu S.S., Wu G.: An enhanced neighborhood search algorithm for solving the split delivery vehicle routing problem with two-dimensional loading constraints, Computers & Industrial Engineering, 2021, Vol. 162, pp. 107720.

- Multi Depot Vehicle Routing Problem (MDVRP): variant of the problem which includes multiple depots[19].
- Clustered Vehicle Routing Problem (CluVRP): variant of the problem where customers are grouped into different clusters. The vehicle which serves clients in a given cluster cannot leave it until all customers in the current cluster have been visited [20].
- Consistent Vehicle Routing Problem (ConVRP): the extension of the problem by imposing that the same vehicle visits the same customers at approximately the same time on each day [21].
- Vehicle Routing Problem with Arrival Time Diversification (VRPATD): the modification of the VRP which aims to the efficiency and security. These objectives are the major concerns in cash-in-transit transportation. The efficiency is achieved by determining shortest routes but the security can be improved by generating dissimilar plans of visit [22].
- Periodic Vehicle Routing Problem (PVRP): the problem where each customer is visited many times and given is the minimum frequency of visits. Each customer is visited at every time period according to given schedule [23].
- Multi Fleet Feeder Vehicle Routing Problem (MFFVRP): the customers are served by heterogeneous fleet of vehicles containing small and large vehicles. For example, the small vehicles can be represented by bicycles or motorcycles. The large vehicles have more capacity but the cost of using them is much greater than smaller vehicles. The small vehicles are reloaded as much as they are capacity or customer orders. The reloading is done in special points using large vehicles [24].

[19] Khairy O.M., Shehata O.M., Morgan E.I.: Meta-heuristic algorithms for solving the multi-depot vehicle routing problem, 2020 2nd Novel Intelligent and Leading Emerging Sciences Conference (NILES), 2020, pp. 276–281.
[20] Anisul Islam Md., Gajpal Y., ElMekkawy T.Y.: Hybrid particle swarm optimization algorithm for solving the clustered vehicle routing problem, Applied Soft Computing, 2021, Vol. 110, pp. 107655.
[21] Stavropoulou F.: The consistent vehicle routing problem with heterogeneous fleet, Computers & Operations Research, 2022, Vol. 140, pp. 105644.
[22] Soriano A., Vidal T., Gansterera M., Doernera K.: The vehicle routing problem with arrival time diversification on a multigraph, European Journal of Operational Research, 2020, Vol. 286, pp. 564–575.
[23] Vega-Figueroa S.E., López-Becerra P.A., López-Santanaa E.R.: Hybrid algorithm for the solution of the periodic vehicle routing problem with variable service frequency, International Journal of Industrial Engineering Computations, 2022, Vol. 13, pp. 277–292.
[24] Salehi Sarbijan M., J. Behnamian J.: Multi-fleet feeder vehicle routing problem using hybrid metaheuristic, Computers & Operations Research, 2022, Vol. 141, pp. 105696.

The current most popular variants of the VRP are Green VRP, Electric VRP and Unmanned VRP described in more detail in Sections 4–6. A review of other studied variants of the VRP is presented in Bhuvaneswari et al. (2018), Braekers et al. (2016), Gupta and Saini (2018), Widuch (2020)[25].

1.4. Green vehicle routing problem

The transportation sector is one of the sources of various types of emissions that have a negative influence on the environment. Thus over the last decade, it is becoming more and more popular to determine routes taking into account the influence of vehicles on the environment. The model of VRP with environmental concern is named as the Green Vehicle Routing Problem (GVRP). The GVRP includes different environmental issues when determining routes, such as Green House Gas (GHG) emission, fuel consumption, noise, pollution, using fleet of Alternative Fuel Vehicles (AFVs), i.e., vehicles that use alternative fuel like methanol, electricity and natural gas, etc.

The GVRP was proposed in 2012[26] where a homogeneous fleet of AFVs is considered and the total traveled distance is minimized. In the paper a difficulties that exists as a result of limited infrastructure of Alternative Fueling Stations (AFSs) are considered. The vertices of the graph represent depot, customers and AFSs. Determined paths include plan of refueling and stops at AFSs to eliminate the risk of running out of fuel while passing the routes. Thus each route may include a stop at one or more AFSs. Refueling policy requires an AFV to leave a refueling station with a full tank. The experiments were carried out using a medical textile supply company depot location in Virginia (VA). A customers were created based on hospital locations in Virginia (VA), Maryland (MD) and the District of Colombia (DC) using Google Earth.

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[25] Bhuvaneswari M., Eswaran S., Rajagopalan S.P.: A survey of vehicle routing problem and its solutions using bio-inspired algorithms, International Journal of Pure and Applied Mathematics, 2018, Vol. 118, pp. 259–264.
Braekers K., Ramaekers K., Nieuwenhuyse I.V.: The vehicle routing problem: state of the art classification and review, Computers & Industrial Engineering, 2016, Vol. 99, pp. 300–313.
Gupta A., Saini S.: On solutions to vehicle routing problems using swarm optimization techniques: A review. [in:] Advances in Computer and Computational Sciences, Singapore, 2018, pp. 345–354.
Widuch J.: Current and emerging formulations and models of real-life rich vehicle routing problems. [in:] Smart Delivery Systems, 2020, pp. 1–35.

[26] Erdoğan S., Miller-Hooks E.: A Green vehicle routing problem, Transportation Research Part E: Logistics and Transportation Review, 2012, Vol. 48, No. 1, pp. 100–114.

A fleet of AFVs is also considered in other papers. In Bruglieri et al.[27] (2019) two Mixed Integer Linear Programming (MILP) formulations to the model are proposed. In the first model, only single visit to AFS between two customers is allowed but in the second model two consecutive visits to AFS are permitted. The goal of the problem is to determine at most m routes of AFV minimizing the total distance. In Bruglieri et al.[28] (2019) a more realistic variant of the GVRP is introduced. The problem with capacitated AFSs is considered where only a limited number of fueling pumps are available at AFS. Thus, the number of refueling vehicles simultaneously at AFS is limited. A heterogeneous AFSs are considered, i.e. the limit may be different for each AFS. In addition, AFSs are divided into two groups: public and private. The private AFSs are owned by the company that owns the AFVs.

A mixed fleet of vehicles containing conventional Gasoline or Diesel Vehicles (GDVs) and AFVs is also considered[29]. There is considered AFVs' limited driving ranges, a sporadic number of AFSs and lengthy refueling. The GDVs represent unrestricted vehicles with respect to AFS's aspects. The AFV may visit one or more AFS but the GDVs visit only customers. The goal of presented problem is to determine set of routes minimizing the total cost of travel.

Since industrial revolution we observe an increase in atmospheric CO_2 emissions. A global emissions of CO2 since 1980 is shown in chart (Fig. 1.2). In last 20 and 10 years, the increment has been around 12% and 6% respectively growing from 370.57 ppm (part per million) in 2001 and 390.63 ppm in 2011 and to 414.73 ppm in 2021.

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[27] Bruglieri M., Mancini S., Pisacane O.: More efficient formulations and valid inequalities for the Green Vehicle Routing Problem, Transportation Research Part C, 2019, Vol. 105, pp. 283–296.

[28] Bruglieri M., Mancini S., Pisacane O.: The green vehicle routing problem with capacitated alternative fuel stations, Computers and Operations Research, 2019, Vol. 112, pp. 104759.

[29] Koyuncu I., Yavuz M.: Duplicating nodes or arcs in green vehicle routing: A computational comparison of two formulations, Transportation Research Part E, 2019, Vol. 122, pp. 605–623.

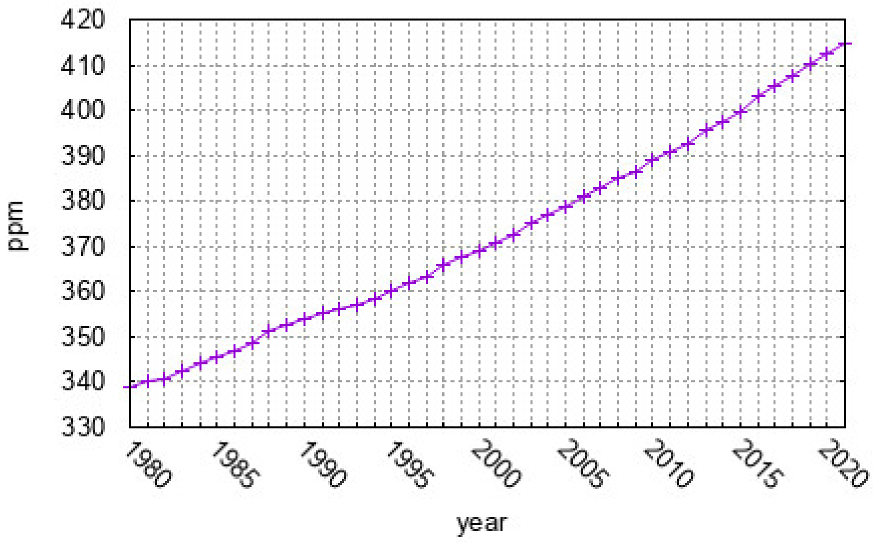

Fig. 1.2. Global CO_2 emission since 1980
Rys. 1.2. Globalna emisja CO_2 od roku 1980[30]

The most popular objective in the GVRP is to reduce CO_2 emissions. In Ferreira et al.[31] (2021) three variants of 2L-CVRP are researched: allowing split delivery (2L-SDVRP), green variant (G2L-CVRP) and hybrid of split delivery and green requirements (G2L-SDVRP). The goal of green variants of the problem is to reduce the CO_2 emissions, the total distances of the routes are not considered. The amount of CO_2 emissions is determined based on following parameters: the CO_2 emission rate per liter of fuel consumed, the fuel consumption rate with the vehicle fully loaded and the fuel consumption with the empty vehicle. Mentioned parameters depend on travel speed, type of vehicles and terrain conditions.

The GVRP is also considered as a Multi-Objective Optimization (MOO) problem where three objectives are minimized simultaneously[32]. The first criterion defines the difference between the largest and shortest distance of all routes. The second criterion represents to total costs and the last criterion is related to the CO_2 emissions to the fuel consumption of vehicles. Another MOO problem is presented in paper Dukkanci et al.[33] (2019), where the Green Location-Routing Problem (GLRP) is introduced. In the GLRP

[30] Source: https://gml.noaa.gov/ccgg/trends/global.html.
[31] Ferreira K.M. Queiroz T.A., Toledo F.M.B.: An exact approach for the green vehicle routing problem with two-dimensional loading constraints and split delivery, Computers and Operations Research, 2021, Vol. 136, pp. 105452.
[32] Londono J.F.C., Rendon R.A.G., Ocampo E.M.T.: Iterated local search multi-objective methodology for the green vehicle routing problem considering workload equity with a private fleet and a common carrier, International Journal of Industrial Engineering Computations, 2021, Vol. 12, pp. 115–130.
[33] Dukkanci O., Kara B.Y., Bektaş T.: The green location-routing problem, Computers and Operations Research, 2019, Vol. 105, pp. 187–202.

given is a set of potential depots with operating costs and a set of customers with known demands. The problem consists of locating depots from where vehicles will be dispatched to serve the customers. The objective is to minimize three objectives: a total cost, fuel consumption and CO_2 emissions. Presented algorithm was tested using a data containing selected cities of the United Kingdom with real road distances but client demands were randomly generated. In Kirci[34] (2019) the GVRP with Time Windows (GVRPTW) is considered. Presented solutions are tested using real scenarios in Turkey.

In Wang et al.[35] (2022) the Multi Depot GVRPTW (MDGVRPTW) is presented where the objective is to minimize carbon emissions. The carbon emission reduction potential of the multi depot model over the single depot model is considered. The algorithms were tested using the Solomon benchmark instances[36]. The results of tests shown that using multi depot in the VRP can reduce carbon emissions by at most 37.6%. The paper Qin et al.[37] (2019) proposes vehicle routing optimization model with adaptive vehicle speed. Presented model is a hybrid of path optimization and speed optimization. The objective is to select optimal speed of vehicle and minimize distribution cost which consists of driver salary, transportation cost, carbon emissions cost and penalty cost when the vehicle violates the time window.

The paper Qin et al.[38] (2019) introduces the carbon tax into the VRP to calculate carbon emissions cost. Other cost items consist of fixed cost of vehicles, transportation cost and penalty cost when the vehicle violates the time windows required by the customer. The objective of the problem is to minimize the total cost. The test were carried out based on a real case data from a company Yanjing Beer Co. Ltd (Shunyi District, Beijing, China) which recycles empty beer bottles.

The impact of route optimization of heavy vehicles on fuel consumption and GHG emissions is also considered[39]. The regular routes of two trucks of Blacktown City (Australia) were extracted and compared with the optimized distances from the simulated model. The results shown that the distance can be reduced by 60%, fuel consumption by 62% and GHG emissions by 62% per month.

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[34] Kirci P.: A novel model for vehicle routing problem with minimizing CO2 emissions, 3rd International Conference on Advanced Information and Communications Technologies (AICT), 2019, pp. 241–243.
[35] Wang S., Han C., Yu Y., Huang M., Sun W., Kaku I.: Reducing carbon emissions for the vehicle routing problem by utilizing multiple depots, Sustainability, 2022, Vol. 14, No. 3, pp. 1264.
[36] https://www.sintef.no/projectweb/top/vrptw/solomon-benchmark/
[37] Qin G.Y., Tao F.M., Li L.X.: A Green vehicle routing optimization model with adaptive vehicle speed under soft time window, 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2019, pp. 1–5.
[38] Qin G., Tao F., Li L., Chen Z.: Optimization of the simultaneous pickup and delivery vehicle routing problem based on carbon tax, Industrial Management & Data Systems, 2019, Vol. 119, No. 9, pp. 2055–2071.
[39] Karimipour H., Tam V.W.Y., Le K.N., Burnie H.: Routing on-road heavy vehicles for alleviating greenhouse gas emissions, Cleaner Engineering and Technology, 2021, Vol. 5, pp. 100325.

Authors of the paper Soon et al.[40] (2019) propose optimization of traffic light control to balance traffic flow. This strategy is developed to minimize GHG emissions and urban congestion. When the traffic congestion is detected then the traffic lights on the congested roads are coordinated to generate green wave scenarios. To avoid the spread of congestion towards upstream roads, a cooperative routing scheme is used to probabilistically distribute vehicles away from the congested road. A fuel consumption and GHG emissions depend on acceleration and speed of vehicles therefore proposed method reduces frequency of acceleration. Proposed methods were tested based on Singapore traffic data. The results shown reducing CO_2 by 37.7%, fuel consumption by 37.6%, travel time by 47.5% and waiting time by 57.3%. The number of arrived vehicles at designated destination were increased by 62.6%.

The emissions depend on fuel consumption. The objective of problem presented in Zarouk et al.[41] (2022) is minimizing fuel consumption and maximizing customer satisfaction derived from the provision of sufficient and timely requests. Both objectives must be simultaneously satisfied thus the problem is solved as MOO problem. Considered model considers a set of heterogeneous vehicles where each vehicle is characterized by a fuel consumption rate lit/km. A similar MOO is researched in Erdoğdu and Karabulut[42] (2022). The objective is to simultaneously minimize the total distance and the total fuel consumption of all vehicles.

In Hou et al.[43] (2021) a problem of energy consumption is considered in the time dependent networks. In the network the vehicle travel time depends on the characteristics of the road network speed. The objective is to minimize the sum of vehicle fixed cost, fuel consumption cost and time window penalty cost. The influence of time dependent networks on routes optimization and the relationship between fuel consumption and vehicle load is researched. In Zhu and Hu[44] (2019) the situation of waiting at customers to avoid bad traffic is proposed. The objective is to find set of optimal routes and the optimal waiting times at each customer nodes with minimum total cost which includes fuel consumption.

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[40] Soon K.L., Lim J.M.-Y., Parthiban R.: Coordinated traffic light control in cooperative green vehicle routing for pheromone-based multi-agent systems, Applied Soft Computing Journal, 2019, Vol. 81, pp. 105486.

[41] Zarouk Y., Mahdavi I., Rezaeian J., Santos-Arteaga F.J.: A novel multi-objective green vehicle routing and scheduling model with stochastic demand, supply, and variable travel times, Computers & Operations Research, 2022, Vol. 141, pp. 105698.

[42] Erdoğdu K., Karabulut K.: Bi-objective green vehicle routing problem, International Transactions in Operational Research, 2022, Vol. 29, pp. 1602–1626.

[43] Hou D., Fan H., Ren X.: Multi-depot joint distribution vehicle routing problem considering energy consumption with time-dependent networks, Symmetry, 2021, Vol. 13, pp. 2082.

[44] Zhu L., Hu D.: Study on the vehicle routing problem considering congestion and emission factors, International Journal of Production Research, 2019, Vol. 57, No. 19, pp. 6115–6129.

When vehicles passing through long distances to serve client demands it may halt at refuelling stations. The time and the cost associated with these visits have an influence on the total cost of the route. The Green VRP with Queues (GVRP-Q) is introduced in paper Poonthalir and Nadarajan[45] (2019). The problem aims to serve a set of customers but includes refuelling time in the refuelling stations where refuelling stations are modelled as M/M/1 model. The impact of refuelling time on the total cost of the route is researched and the objective is to minimize the total cost.

1.5. Electric vehicle routing problem

The variant of VRP where the customers are visited by a fleet of electric vehicles (EVs) is named as the Electric VRP (EVRP). It uses a eco-friendly green vehicles therefore it can be viewed as a variant of the GVRP. The EVs have limited driving range and long charging time therefore when planning routes for EVs it is necessary to predict the energy consumption and plan visits at charging stations in the route. The EVs have shorter driving range than traditional combustion engine vehicles (CEVs) and the availability of charging stations is limited compared to the petrol stations. The charging time of an EV is much longer than the time of refuelling a CEV. In contrast to CEVs, the time of charging cannot be omitted.

The charging of EVs is an important issue and it determines their use. It is widely studied and many constraints are assumed. In Euchi and Yassine[46] (2022) the EVRP wit fixed heterogeneous fleet is considered. A recharging of the battery at any customer for a certain period is allowed. A vehicle can leave a depot with fully charged battery. The objective is to minimize total cost which contains the travelling cost proportional to the travelled distance and the recharging cost which is proportional to the period of recharging the battery. Another objective is considered in Hesam Sadati et al.[47] (2022). The paper presents the EVRP with homogenous fleet of EVs which serve customers with known demands and alternative delivery points and time windows. The order of customer is delivered to exactly one of defined locations. A recharging of EVs only at

[45] Poonthalir G., Nadarajan R.: Green vehicle routing problem with queues, Expert Systems With Applications, 2019, Vol. 138, pp. 112823.
[46] Euchi J., Yassine A.: A hybrid metaheuristic algorithm to solve the electric vehicle routing problem with battery recharging stations for sustainable environmental and energy optimization, Energy Systems, 2022.
[47] Hesam Sadati M.E., Akbari A., Çatay B.: Electric vehicle routing problem with flexible deliveries, International Journal of Production Research, 2022, pp. 1–27.

the company owned depot is allowed but the EV can leave the depot with 90% of battery capacity. The goal of the problem is to minimize the total travelled distance and number of used vehicles. Computational experiments were carried out based on data of U.K. retailer serving 40 customers in East Midlands area. The results shown a reduction of the total distance by 23% and the fleet size by 20%.

A new generation of charging batteries is Wireless Charging Technology (WCT). The system uses innovative technology developed by KAIST in South Korea[48]. The battery can be wirelessly charged from the transmitters using the noncontact charging mechanism. Each transmitter consists of an inverter and inductive cables which generate a magnetic field to charge the battery. When the vehicle runs in the area where inductive cables are installed then the battery is charged until it reach its maximum capacity. In the paper Elbaz and Alaoui[48] (2022) is considered a problem how to install the power transmitters to guarantee to each vehicle a battery capacity between its minimal and maximal level. In Wang et al.[49] (2022) a hybrid charging method is discussed which combines traditional Plug-in Charging Technology (PCT) and WCT. The availability of charging stations both types may vary over time due to the allocation or equipment maintenance. Therefore while planning routes it is not only need to determine optimal routes with minimal travel cost but also to determine the most efficient charging strategy.

The alternative method of charging EVs is battery swapping[50]. It is the only way of supplement energy of EVs. There are two kinds of vehicles and two kinds of routes are determined. For the EVs determined are routes to deliver demands to the set of customers. The second kind of routes are determined to the special Battery Swap Vehicles (BSVs) to swap depleted batteries on EVs with a fully charged at a designated place and time. The BSVs are electric vehicles and are only used to swap battery in EVs, they are not allowed to swap battery in another BSV. In addition, the BSVs cannot be used to serve demands to customers. There is challenging problem of synchronization between two kinds of vehicles, i.e. EVs and BSVs. The problem is considered as MOO problem, the goal is to minimize a total cost of using EVs and BSVs and the total

[48] Elbaz H., Alaoui A.E.: Optimal installation of the power transmitters in the dynamic wireless charging for electric vehicles in a multipath network with the round-trip case, International Journal of Intelligent Transportation Systems Research, 2022, Vol. 20, pp. 46–63.

[49] Wang Z., Ye K., Jiang M., Yao J., Xiong N.N., Yen G.G.: Solving hybrid charging strategy electric vehicle based dynamic routing problem via evolutionary multi-objective optimization, Swarm and Evolutionary Computation, 2022, Vol. 68, pp. 100975.

[50] Raeesi R., Zografos K.G.: The electric vehicle routing problem with time windows and synchronised mobile battery swapping, Transportation Research Part B, 2020, Vol. 140, pp. 101–129.

distance travelled by them. Another problem is considered in Zhou and Zhao[51] (2022). The BSVs are not available and the EV needs to visit the Battery Swap Station (BSS) to swap its battery. There is only one BSS but its capacity is unlimited. It is assumed that each EV can swap the battery at most once during passing a route and the impact of the load of EV on the battery power consumption is omitted. The objective of the problem is to minimize the total distribution costs and maximize utilization of batteries. In Li et al.[52] (2020) is considered a problem of battery swapping where many BSSs are available. The EV is allowed to visit the BSS one or more times. The objective is to minimize the total cost which contains the cost of using EV and power consumption.

In Iwańkowicz[53] (2021) a battery lifetime is considered while planning the routes. The vehicle can leave a charging station when batteries are charged to 80%. A battery charging time is nonlinear. It has been shown that the time of charging from 80% to 100% is so long and it is more effective to charge it more frequently to the 80% level than charge it less frequently to the 100% level. Presented methods were tested based on real data containing points located in north-western Poland: single depot located in Stargard City, four charging points located in small cities and 28 customers.

The paper Lin et al.[54] (2021) presents the EVRP where the scheduling of charging the EVs from the charging stations and discharging to the charging stations are considered. The EV can stop at the station to charge the batteries but it can also inject stored energy to the grid. The objective is to determine an optimal schedule of charging and discharging based on the energy price which depend on time-of-use. The energy demands can be shifted from peak hours to off-peak hours when the cost of energy is lower. At high price periods the EVs can recover cost of energy by injection it to the grid. The tests were carried out using a real data of the fleet which serve demands to the customers at the region of Kitchener-Waterloo in Ontario (Canada).

In Macrina et al.[55] (2019) the problem with a mixed fleet containing conventional CEVs and EVs is presented. Since a full battery charging requires a long time the possibility of recharging batteries partially at any available recharging station is allowed.

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[51] Zhou B., Zhao Z.: Multi-objective optimization of electric vehicle routing problem with battery swap and mixed time windows, Neural Computing and Applications, 2022.
[52] Li J., Wang F., He Y.: Electric vehicle routing problem with battery swapping considering energy consumption and carbon emissions, Sustainability, 2020, Vol. 12, pp. 10537.
[53] Iwańkowicz R.: Effective permutation encoding for evolutionary optimization of the electric vehicle routing problem, Energies, 2021, Vol. 14, pp. 6651.
[54] Lin B., Ghaddar B., Nathwani J.: Electric vehicle routing with charging/discharging under time-variant electricity prices, Transportation Research Part C, 2021, Vol. 130, pp. 103285.
[55] Macrina G., Di Puglia Pugliese L., Guerriero F., Laporte G.: The green mixed fleet vehicle routing problem with partial battery recharging and time windows, Computers and Operations Research, 2019, Vol. 101, pp. 183–199.

The objective is to minimize a total cost which consists of four components: the cost of recharging at charging stations, a vehicle activation cost which depends on the battery capacity, the cost of routes travelled by EVs and CEVs. In Chen et al.[56] (2021) the problem with mixed fleet is also presented but the only way of supplement energy of EVs during passing the route is battery swapping. A depot is only one place where the vehicles are recharged at the night. The vehicle starts its route with a fully charged battery.

In the paper Basso et al.[57] (2021) an energy consumption estimation is considered. Proposed estimation model considers vehicle speed, topography, powertrain efficiency and the effect of braking and acceleration. Presented methods were tested using real road network from Gothenburg (Sweden) and the results of estimation were compared with real data from public transport route. The maximum error of estimation was less than 5% while the average error was 2.28%.

A real-word charging infrastructure is also analysed as EVRP. In Hecht et al.[58] (2021) a charging infrastructure in Germany, a leading adopter of EVs in Europe, is evaluated by analysing travel time for five EVs on 60 routes passed through Germany. Based on evaluation the final conclusions are formulated. Total travel time is an average of 8% more due to battery recharging. On average, a single stop for charging takes about 14 minutes and the average time between two charges is 90 minutes. Range optimization by 30% makes possible to obtain the travel time comparable to traditional CEV. It can be reached by optimising driving behaviour. A charging infrastructure makes possible to reach destination points without running out of battery power and violating defined constraints.

The battery life of EV decreases with the increase of charging times and at some point it reaches its end of life. There is a problem of used batteries utilization. Recycling and reuse of the batteries reduce its the influence to the environmental pollution. Therefore the challenge is to building a recycling network and it is a critical for using the EVs. In Hu et al.[59] (2022) three strategies to deal with used batteries are analysed: remanufacturing, reuse and recycling materials. A model of recycling network is

[56] Chen Y., Li D., Zhang Z., Wahab M.I.M., Jiang Y.: Solving the battery swap station location-routing problem with a mixed fleet of electric and conventional vehicles using a heuristic branch-and-price algorithm with an adaptive selection scheme, Expert Systems With Applications, 2021, Vol. 186, pp. 115683.
[57] Basso R., Kulcsár B., Egardt B., Lindroth P., Sanchez-Diaz I.: Energy consumption estimation integrated into the Electric Vehicle Routing Problem, Transportation Research Part D, 2019, Vol. 69, pp. 141–167.
[58] Hecht Ch., Victor K., Zurmühlen S., Sauer D.U.: Electric vehicle route planning using real-world charging infrastructure in Germany, eTransportation, 2021, Vol 10, pp. 100143.
[59] Hu X., Yan W., Zhang X., Feng Z., Wang Y., Ying B., Zhang H.: LRP-based design of sustainable recycling network for electric vehicle batteries, Processes, 2022, Vol. 10, pp. 273.

proposed where the goal is to minimize the total cost and carbon emissions. The model was validated based on GEM company (a Chinese company of recycling and reuse) as an example.

In Erdem[60] (2022) the Electric Vaste Collection Problem (EWCP) is introduced. In EWCP a heterogeneous fleet of EVs is used to visits a customers where the waste bins are located. The problem is researched on the real-world case in Samsun (Turkey) where the collection of recycling wastes (plastic, metal, paper and glass) and used cooking oil are considered.

1.6. Unmanned vehicle routing problem

Over the past few year Unmanned Aerial Vehicles (UAVs), or drones, have become more and more popular and find application in many fields. This type of vehicles have the potential to reduce the cost and the time of delivery. UAVs are not limited by roads infrastructure therefore delivering with UAVs may be faster than delivering with traditional vehicles. It can be used to deliver parcels, food or medical supplies over dangerous area thus it has a potential to save lives in critical situations like war or time of natural disaster. In 2013 Amazon revealed plans for Prime Air which assumed delivering by UAVs packages under 2.5 kg in less than 30 min[61].

The paper Rajan et al.[62] (2022) presents a problem of using UAVs in patrolling missions. Given are two kinds of targets: primary targets and supplemental targets where a given number of supplemental targets correspond to each primary target. The main goal is to determine a path which visits each primary target. After visiting the primary target the UAV sends collected information to the operator. If the operator deems that the information is insufficient then UAV visits all supplemental targets corresponding to visited primary target and collects additional information before it visits the next primary target. The objective is to minimize the total cost of traversing the path.

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[60] Erdem M.: Optimisation of sustainable urban recycling waste collection and routing with heterogeneous electric vehicles, Sustainable Cities and Society, 2022, Vol. 80, pp. 103785.
[61] Deng X., Guan M., Ma Y., Yang X., Xiang T.: Vehicle-assisted UAV delivery scheme considering energy consumption for instant delivery, Sensors, 2022, Vol. 22, pp. 2045.
[62] Rajan S., Sundar K., Gautam N.: Routing problem for unmanned aerial vehicle patrolling missions – a progressive hedging algorithm, Computers & Operations Research, 2022, Vol. 142, pp. 105702.

Another problem is studied in Shen et al.[63] (2022). The paper focuses on a multi--drone path planning problem where a given set of drones collect a data from a set of points in a determined area. The goal of the problem is to maximize the number of visited point and eliminate flight path intersections to avoid drone collisions in flight. There are two solutions to avoid collision. In the first case a set of paths is determined and all possible collisions are eliminated. In the second case during planning paths possible collisions are detected and eliminated and a set of collision-free paths is determined. The authors focuses on the second method.

In Wang et al.[64] (2020) a cooperative path planning of UAV swarm with dynamic customer arrivals in a set of potential locations and waiting deadlines is presented. The objective is to determine optimal paths for set of UAVs maximizing the total number of successfully served customers. The cooperation of UAVs is an important part of path planning. The UAV needs to decide whether to wait in the current location or chase a new location, with a coordination with the other available UAVs.

In Ragab et al.[65] (2022) the UAVs are researched as a component of smart city. A drone has a various smart devices which consists of different sensors like time-of flight sensor, magnetic field change sensor, thermal and chemical sensor and orientation sensor. Drones are remotely controlled and often move without human control. Proposed conception of Internet of Drones (IoD) is a technique where a set of drones, where each of them serves a given flight area and executes a special procedure which communicate and sends a data via sensors to dedicated control server. It assumes that the users can monitor any drones via own mobile phone and trusted control server in a flying area. Drones have limited battery resources that have influence to the efficiency of data transmission and communication in IoD. Therefore a significant problem is the development of an effective data transmission which is a challenging process. There is proposed a hierarchal routing also named clustering where the network is divided into subgroups. A cluster contains cluster members and cluster head (CH), which is selected among all members. The CH controls the performance of the cluster. In the paper an efficient grouping drones in the cluster enabling optimal data transmission via shortest routes is studied.

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[63] Shen K., Shivgan R., Medina J., Dong Z., Rojas-Cessa R.: Multi-depot drone path planning with collision avoidance, IEEE Internet of Things Journal, 2022, pp. 1–1.

[64] Wang K., Zhang X., Duan L.: Cooperative path planning of a UAV swarm to meet temporal-spatial user demands, GLOBECOM 2020 - 2020 IEEE Global Communications Conference, 2020, pp. 1–6.

[65] Ragab M., Altalbe A., Al-Malaise ALGhamdi A.S., Abdel-khalek S., Saeed R.A.: A drones optimal path planning based on swarm intelligence algorithms, Computers, Materials & Continua, 2022, Vol 72, No. 1, pp. 365–380.

The paper Chen et al.[66] (2022) presents delivery with mixed fleet containing traditional vehicles and drones. Clients make delivery requests over the day and the operator dynamically dispatches drones and vehicles to serve clients before defined delivery deadline. Vehicles can deliver multiple packages but due to the road traffics the deliver is slowly. Drones have limited capacity and require charging the battery but the time of delivery is faster. The operator must determine whether a delivery request can be served and, if so, it decides which type of vehicle, i.e. traditional or drone, will serve it. The goal of the problem is to maximize the number of served clients per day. A similar problem is presented in Nguyen et al.[67] (2022) but the objective is to minimize a total transportation cost. It assumes that a traditional vehicle can serve many customers passing a single trip. A drone serves only single customer in the trip and returns to the depot. It should be pointed out that not all delivers can be served by drones and some must be served by traditional vehicle. In Coindreau et al.[68] (2021) is considered a problem of delivery using mixed fleet of vehicles where drones are embedded into the truck but the truck is embedded with a maximum one drone. Drones are loaded with a parcels and launched directly from the truck. Drones serve clients and autonomously return to the truck where are charged and reloaded. Drone can transport only one parcel at a time. If parcel is to heavy or if drone landing is impossible then a parcel is delivered by a truck. Presented model was inspired by a large European logistic provider[69]. The tests were carried out based on real data of the provider. The results shown that a total cost of fuel consumption by the truck can be reduced at least 15% when the percentage number of clients reachable by drone is above 50%. For instances containing 50 or 100 clients where each client was reachable by drone the cost reduction was between 20% and 35%.

Another cooperation traditional vehicles and UAVs is presented in Deng et al.[70] (2022). Customers are divided into clusters where each cluster has single stopping point. The vehicle carrying multiple UAVs from distribution center and traverses determined route which contains stopping points. When vehicle reaches stopping point multiple UAVs take-off at the same time and deliver parcels to the customers and return to the

[66] Chen X., Ulmer M.W., Thomas B.W.: Deep Q-learning for same-day delivery with vehicles and drones, European Journal of Operational Research, 2022, Vol. 298, pp. 939–952.
[67] Nguyen M.A., Thi-Huong Dang G., Hoàng Hà M., Minh-Trien Pham: The min-cost parallel drone scheduling vehicle routing problem, European Journal of Operational Research, 2022, Vol. 299, pp. 910–930.
[68] Coindreau M.-A., Gallay O., Zufferey N.: Parcel delivery cost minimization with time window constraints using trucks and drones, Networks, 2021, Vol. 78, pp. 400–420.
[69] The name of the provider is not published as per a nondisclosure agreement.
[70] Deng X., Guan M., Ma Y., Yang X., Xiang T.: Vehicle-assisted UAV delivery scheme considering energy consumption for instant delivery, Sensors, 2022, Vol. 22, pp. 2045.

vehicle. In presented model single UAV can deliver multiple parcels to many customers in single flight. The vehicles are only used as a mobile warehouses and charging stations.

The paper Qin et al.[71] (2021) focuses on the charging problem of UAVs. The given fleet of UAVs start from base and conduct missions by visiting a set of target points. Proposed charging model bases on Mobile Charging Vehicles (MCVs). Simultaneously with UAVs the MCVs travel to special charging points located at the routes of the UAVs where UAVs are charged wirelessly. In the paper optimization routes of MCVs is researched where the objective is to minimize the total cost power supply and maximize completion quality of UAVs missions.

Using UAVs is also studied as a green routing model[72]. The UAV yield lower energy consumption than traditional vehicles and its using reduces greenhouse gas emissions. The paper focusses on the impact of cooperating UAVs with traditional combustion vehicles on CO_2 emission. As the number customers increases, the number of required vehicles and CO_2 emissions also increase. The results of experiments shown that the 300, 400 and 500 customers instances require one fewer traditional vehicle when UAVs are used. On average, the emission of CO_2 was reduced about 20%. For the 200 customers instance the emission of CO_2 was reduced about 16%.

In Wang et al.[73] (2022) a global path planning for Unmanned Surface Vehicles (USVs) is presented. The USV has high speed, intelligence, low cost and no risk of casualty. It can carry different loads thus it can be used to serve clients in civilian fields. It has also good concealment and resistance to extreme conditions therefore it is useful in military area. Global path planning is applied in the USV self-navigation to determine a safe and anti-collision path between source and destination points. Presented methods were tested in a 3 × 3 km maritime environment with 30 × 30 grid environment model.

The UAVs are applied in diverse environments. The paper Ribeiro et al.[74] (2020) presents using the UAVs in the mining industry. The UAVs are used to handle periodic inspections of the belt conveyors that transport iron ore. The goal is to determine the best route for inspections minimizing to total cost of operation. The tests were carried

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[71] Qin W., Shi Z., Li W., Li K., Zhang T., Wang R.: Multiobjective routing optimization of mobile charging vehicles for UAV power supply guarantees, Computers & Industrial Engineering, 2021, Vol. 162, pp. 107714.
[72] Chiang W.-C., Lib Y., Shang J., Urban T.L.: Impact of drone delivery on sustainability and cost: Realizing the UAV potential through vehicle routing optimization, Applied Energy, 2019, Vol. 242, pp. 1164–1175.
[73] Wang H., Zhang J., Dong J.: Application of ant colony and immune combined optimization algorithm in path planning of unmanned craft, AIP Advances, 2022, Vol. 12, pp. 025313.
[74] Ribeiro R.G., Júnior J.R.C., Cota L.P., Euzébio T.A.M., Guimarães F.G.: Unmanned aerial vehicle location routing problem with charging stations for belt conveyor inspection system in the mining industry, IEEE Transactions on Intelligent Transportation Systems, 2020, Vol. 21, No. 10, pp. 4186–4195.

out based on a real data of conveyor belt system in Brazil. The system consists of the loading terminal and 120 km of belt conveyors leading to 230 inspection points. In Grogan et al.[75] (2021) using the UAVs with wireless sensors and cameras to exploring and preparing search and rescue operation on an area after the occurrence of a tornado. Presented method consists of two steps. The aim of the first step is to generate a set of waypoints that must be visited. The second step contains determining a route that visits set of waypoints minimizing the longest tour of the UAV. Presented method was tested based on a real data from the National Oceanic and Atmospheric Administration and Geographic Information System data from the states of Oklahoma and Texas, USA. The paper Liperda et al.[76] (2020) focuses on the use of drones to monitoring flooded areas. The objective is to minimizing the total time required to perform operations. The object of researching was Bekasi city in Indonesia, which was affected by flooding in February 2020. This city is categorized in the high-risk class with a score of 33.6 against flood disasters. The paper Ozkan[77] (2021) proposes a method of determining a route of UAVs to mitigate forest fire risks. The researching was carried out based on fire-risk maps countrywide generated every day by the Turkish State Meteorological Service. The maps make possible to predict fire risk 3 days later based on meteorological data. The author proposes a method of determining the risky regions based on these maps that will be visited by the UAVs.

1.7. Conclusions

This chapter presents the limited review on current variants of the VRP. The vast majority of the analyzed papers in the chapter come from the last 5 years. The studied problems are based on real transport systems. A real-life characteristics are often considered either individually or with a limited number of characteristics. New trends, which are the reduction of the negative impact on the environment, pollution and

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[75] Grogan S., Pellerin R., Gamache M.: Using tornado-related weather data to route unmanned aerial vehicles to locate damage and victims, OR Spectrum, 2021, Vol. 43, pp. 905–939.

[76] Liperda R.I., Pewira Redi A.A.N., Sekaringtyas N.N., Astiana H.B., Sopha B. M., Maria Sri Asih A.: Simulated annealing algorithm performance on two-echelon vehicle routing problem-mapping operation with drones, 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2020, pp. 1142–1146.

[77] Ozkan O.: Optimization of the distance-constrained multi-based multi-UAV routing problem with simulated annealing and local search-based matheuristic to detect forest fires: The case of Turkey, Applied Soft Computing, 2021, Vol. 113, pp. 108015.

greenhouse gas emissions, are more and more often taken into account in the analyzed problems. The ecological aspects are resolved by using a vehicles with alternative energy source.

Future research could look at problems that take into account both new types of vehicles and new emerging features of transport systems. Taking into account more and more characteristics makes problem solving methods more and more complicated. The VRP and their variants are known as NP-hard problems and they are solved using various heuristics methods. Therefore, the research focuses on the development of more and more effective methods enabling the determination of the solution closest to the optimal one.

DOI:10.34918/87422

Zbigniew CZAPLA[1]

2. TRAVEL PARAMETERS ON URBAN BUS ROUTES INTENDED FOR OPERATION WITH ELECTRIC BUSES PROPELLED BY TRACTION BATTERIES

2.1. Introduction

Collective bus transport is used in many cities. At present, on urban bus routes, increasingly electric buses propelled by traction batteries are utilized. Operation of electric buses causes reduction of exhaust emissions and decreases air pollution in cities, especially in city centres. The main disadvantage in the operation of electric buses propelled by traction batteries is their range which significantly depends on capacity of traction batteries and current energy consumption. When the electric bus is driving, the energy consumption is variable and results from travel parameters. The travel parameters depends on many factors such the topology of a bus route, a height profile along a bus route, ambient temperature, traffic volume, a driving style, timetables, a number of stops, queuing and bunching.

The electric energy consumption of electric vehicles can be predicted[2]. The presented approach is based on statistical models of energy consumption and considers the correlation of electric energy consumption and kinematic parameters of vehicle movement. It is reliable to compare vehicles of the same type propelled by a battery electric engine and an internal combustion engine[3]. The comparison includes energy consumption in various driving scenarios.

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[2] De Cauwer C., Van Mierlo J., Coosemans T.: Energy consumption prediction for electric vehicles based on real-world data, Energies, 2015, Vol. 8, pp. 8573–8593.

[3] Braun A., Rid W.: Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real word data on the Erfurt circuit in Germany, Transportation Research Procedia, 2017, Vol. 27, pp. 468–475.

Automatic location data for bus lines and automated vehicle data for urban areas can be collected and then used to model the travel time and determine its fluctuation[4]. Historical profiles enable the prediction of bus travel time[5]. For the prediction of short term travel time, historical behaviour and current travel time at points of interest are analysed.

GPS data are useful for predicting bus travel time[6]. Travel time is predicted with the use of models based on historical average, Kalman filtering, and artificial neural networks, and then the accuracy and robustness of the analysed models are compered. Machine learning methods are applied for the prediction of bus travel time[7]. Bus travel time and bus speed are predicted on the basis of GPS data and with the use of implemented artificial neural networks, support vector machines, and Bayes networks and then compered. The bus travel time between stations can be predicted using a support vector machine[8]. The prediction of the bus travel time is performed using GPS data and the division of road sections into segments.

The accuracy of GPS data is a complex issue and various methods for improving GPS data inaccuracy are considered and analysed[9]. To improve the inaccuracy of GPS data, reference station networks methods, software algorithms, and perceptive GPS are used.

The bus travel time on urban bus routes can be analysed using GPS data[10]. The considered bus route is divided into two types of sections, stopping sections and running sections. For individual sections and the entire bus route, the stopping and running times are estimated on the basis of GPS data. The assumption of the utilization of GPS data and the division of the urban bus route into stopping and running section also allows for the description of urban bus routes by movement parameters[11]. The stopping sections are described by the stopping time, and for the running sections, the stopping time, the time at constant speed, and the times of acceleration and deceleration are determined.

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[4] Comi A., Nuzzolo A., Brinchi S., Verghini R.: Bus travel time variability: some experimental evidences, Transportation Research Procedia, 2017, Vol. 27, pp. 101–108.
[5] Cristobal T., Padron G., Quesada-Arencibia A., Alayon F., de Blasio G., Garcia C.R.: Bus travel time prediction model based on profile similarity, Sensors 2019, Vol. 19:2869.
[6] Fan W, Gurmu Z.: Dynamic travel time prediction models for buses using only GPS data, International Journal of Transportation Science and Technology, 2015, Vol. 4, No. 4, pp. 352–366.
[7] Julio N., Giesen R, Lizana P.: Real time prediction of bus travel speeds using traffic shockwaves and machine learning algorithms, Research in Transportation Economics, 2016, Vol. 59, pp. 250–257.
[8] Junyou Z., Fanyu W., Shufeng W.: Application of support vector machine in bus travel time prediction, International Journal of System Engineering, 2018, Vol. 2, No. 1, pp. 21–25.
[9] Thin L.N., Thin L.Y., Husna N.A., Husin M.H.: GPS systems literature: inaccuracy factors and effective solutions, International Journal of Computer Networks & Communication, 2016, Vol. 8, No. 2, pp. 123–131.
[10] Czapla Z., Krawiec S.: GPS data-based estimation of travel time parameters for electric buses, [in:] Stajniak M. et al. (eds): Challenges and modern solution in transportation. Spatium, Radom, 2019, pp. 135–146.
[11] Czapla Z., Krawiec S.: Travel time description for urban routes operated with electric buses, [in:] Rozicka J. (ed.): Smart Cities Symposium Prague. IEEE, 2020.

In the proposed method of determining the travel parameters on urban bus routes, GPS data are used. The considered urban bus route is divided into sections with a uniform structure. For each section and the entire urban bus route, the travel time is determined by assigning the bus speed to the defined speed ranges. The goal of the work is the determination of travel parameters based on GPS data for urban bus routes intended for operation with electric buses propelled by traction batteries. The travel parameters are calculated using the distribution of the speed of the bus along the bus route. The energy consumption of the bus driving on the bus route depends on its speed and travel time. The calculated times of the bus speed from individual speed ranges indicates the energy demand on the considered bus route and allow for the assessment of its suitability for operation with electric buses. The determined travel parameters are related to the energy consumption of electric buses and can be useful for planning charging and preparing timetables.

2.2. Principle of the method

The considered bus route is divided into sections. The division into section is based on the layout of the bus stops. The sections are disjoint and they cover the entire bus route. Each section consists of a part of the bus route between two neighbouring bus stops. To the section also belongs the bus stop to which a bus goes. The bus begins to drive on the next section when it starts to move from the bus stop.

The bus moving along a bus route is equipped with a GPS receiver. The GPS receiver determines the location data of consecutive track points with a constant frequency. The location data of individual track points are recorded in a data file. Each track point is described by its ordinal number, the latitude and longitude, and the date and time of measurement.

The distance between two consecutive track points is determined on the basis of their latitude and longitude. Location data are recorded with a constant frequency, and hence the average speed between consecutive track points can be calculated. For each track point the speed is calculated in relation to the previous track point and supplements the location data.

The energy consumption of electric buses depends on many factors. For the bus route considered, the energy consumption of electric buses can be estimated by analysing the bus speed profiles of individual sections. The medium speed is the most beneficial to the energy consumption of electric buses. The energy consumption increases at a speed greater than the medium speed. The increase of the energy consumption also causes the speed which is less than the medium speed. The low speed is usually caused by frequent slowing down and accelerating, that results from traffic conditions. Estimation of the energy consumption of electric buses for the entire bus route can be carried out by aggregation of the data obtained for the individual sections.

2.3. Input data

The input data are location data recorded by a GPS receiver in a data file. The data file is in GPX format that uses an XML schema. A track is recorded and stored in the GPX file and consists of track points. Each track point p_i is described by the set of parameters as follows:

$$p_i = \{i, long_i, latit_i, elev_i, date_i, time_i\}, \tag{2.1}$$

where i is the ordinal number of the track point, $long_i$ is the longitude in decimal degrees, $latit_i$ is the latitude in decimal degrees, $elev_i$ is the elevation above sea level in meters, $date_i$ is the current date and $time_i$ is the current time.

The distance between the current track point i and the track point i–1, which directly precedes the current track point, is given by

$$dist_i \approx \frac{40075.704 \cdot 10^3}{360} \sqrt{(latit_i - latit_{i-1})^2 + [(long_i - long_{i-1}) \cos latit_i]^2} \,. \tag{2.2}$$

The longitude and latitude are given in decimals degree, and then the distance between two consecutive track points is given in meters. The average speed between two consecutive track points is expressed by the equation

$$speed_i \approx \frac{dist_i}{time_i - time_{i-1}} \,. \tag{2.3}$$

The location data are acquired with a constant frequency, and hence the average speed between two consecutive track points can be given by

$$speed_i \approx \frac{dist_i}{T}, \tag{2.4}$$

where T is a time period between two successive acquisitions of the location data. The distance between two consecutive track points is given in meters, and when the time period between two successive acquisitions of the location data is expressed in seconds, the speed at the current track point is given in meters per second.

After the data of the track are supplemented with the distance and the speed, the set of parameters describing the single track point is expressed by

$$p_i = \{i, long_i, latit_i, elev_i, date_i, time_i, dist_i, speed_i\}. \tag{2.5}$$

On the basis of input data, the travel parameters are determined. The travel parameters enable assessment of suitability of the considered urban bus route for operation with electric buses.

2.4. Travel parameters

Travel parameters are calculated on the basis of the speed at individual track points. The distribution of speed data on the bus route depends on many factors, especially on the topology of the bus route and traffic conditions. The speed determined at individual track points is divided into ranges. There are defined four ranges: a zero speed range, a low speed range, a medium speed range, and a high speed range and four speed pointers z_i, l_i, m_i, and h_i, that correspond to appropriate ranges. The initial value of all speed pointers is equal to 0

$$\begin{aligned} z_i &= 0, \\ l_i &= 0, \\ m_i &= 0, \\ h_i &= 0. \end{aligned} \tag{2.6}$$

The assignment of a speed at a single track point is carried out according to the expression

$$\begin{aligned} z_i &= 1 \quad \text{for} \quad speed_i \le v_{z\max}, \\ l_i &= 1 \quad \text{for} \quad speed_i > v_{z\max} \wedge speed_i \le v_{l\max}, \\ m_i &= 1 \quad \text{for} \quad speed_i > v_{l\max} \wedge speed_i \le v_{m\max}, \\ h_i &= 1 \quad \text{for} \quad speed_i > v_{m\max}, \end{aligned} \tag{2.7}$$

where $v_{z\max}$ is the maximum speed for the zero speed range, $v_{l\max}$ is the maximum speed for the low speed range, and $v_{m\max}$ is the maximum speed for the medium speed range. The maximum speed for the zero speed range is defined due to inaccuracy of the location data resulting in a non-zero small speed recorded when a bus is not driving. The speed ranges are disjoint, including all possibly speeds. The maximum speeds of the speed ranges satisfy

$$v_{z\max} < v_{l\max} < v_{m\max}, \tag{2.8}$$

hence for each track point one pointer is equal to 1 only when the others are equal to 0.

The track points are assigned to the sections. Each track point is assigned to exactly one section denoted by the section number j. The track points that belong to the section j have the ordinal numbers limited by a beginning number beg_j and an end number end_j

$$beg_j \le i \le end_j, \tag{2.9}$$

thus the number of truck points N_j included in the section is described by

$$N_j = end_j - beg_j + 1, \tag{2.10}$$

The sections are described by section row vectors $\mathbf{S_j}$ that contain the section number, the number of track points in the section, and the sums of pointers

$$\mathbf{S_j} = \left[j, N_j, \sum_{k=beg_j}^{end_j} z_k, \sum_{k=beg_j}^{end_j} l_k, \sum_{k=beg_j}^{end_j} m_k, \sum_{k=beg_j}^{end_j} h_k \right]. \tag{2.11}$$

Denoting the sums of pointers by Z_j, L_j, M_j, and H_j, respectively, the section row vectors take the form

$$\mathbf{S_j} = \left[j, N_j, Z_j, L_j, M_j, H_j \right]. \tag{2.12}$$

The bus route divided into J sections is described by the section matrix **S** of J rows, each of which describes one section

$$\mathbf{S} = \begin{bmatrix} 1 & N_1 & Z_1 & L_1 & M_1 & H_1 \\ 2 & N_2 & Z_2 & L_1 & M_2 & H_2 \\ & & & & & \\ J & N_J & Z_J & L_J & M_J & H_J \end{bmatrix}. \tag{2.13}$$

After aggregation of data, the entire bus route is described by the route row vector **R** containing sums of all pointers

$$\mathbf{R} = \left[\sum_{j=1}^{J} N_j, \sum_{j=1}^{J} Z_j, \sum_{j=1}^{J} L_j, \sum_{j=1}^{J} M_j, \sum_{j=1}^{J} H_j \right]. \tag{2.14}$$

Denoting the sum of the track points by N, and the sums of pointers Z, L, M, and H, respectively, the route row vector for the entire bus route takes the form

$$\mathbf{R} = \left[N, Z, L, M, H \right]. \tag{2.15}$$

The section matrix **S** and the route row vector **R** contain travel parameters that describe the bus route considered for one ride. For assessment of the suitability of the consider bus route for the operation with electric buses, the travel parameters should be determined for rides in different traffic condition. Each ride gives description of the travel parameters in the form of the section matrix **S** and the route row vector **R**.

2.5. Measurements

The measurements have been carried out on the number 297 bus route in Katowice city. This bus route starts in the centre of Katowice city at the bus terminal near the railway station and leads south to the Odrodzenia housing estate, which is located in the Piotrowice district. From the Odrodzenia housing estate, the bus route heads back to the same bus terminal in the city centre where it starts. The number 297 bus route consists of 26 sections. The sections of intensive traffic are located mostly in the city centre and the sections of low traffic are mainly outside of the city centre. Table 2.1 presents the sections of the number 297 bus route.

In the sections of intensive traffic may occur traffic congestions especially in peak hours. Input data have been acquired during two rides called Ride 1 and Ride 2. Ride 1 has been performed in off-peak hours, and Ride 2 in peak hours. The location data at individual track points have been recorded in the data files with an interval of 1 second. The track of Ride 1 consists of over 3900 track points while the track of Ride 2 of over 4500 track points.

Table 2.1

Sections of the number 297 bus route

Section number	Section name
1	Katowice Dworzec – Katowice Mikołowska
2	Katowice Mikołowska – Katowice AWF
3	Katowice AWF – Brynów W. Pola
4	Brynów W. Pola – Brynów Dworska
5	Brynów Dworska – Brynów Kościuszki
6	Brynów Kościuszki – Brynów Pętla
7	Brynów Pętla – Ochojec Wapienna
8	Ochojec Wapienna – Ochojec Sadowa
9	Ochojec Sadowa – Ochojec Ziołowa
10	Ochojec Ziołowa – Piotrowice Tyska
11	Piotrowice Tyska – Odrodzenia Radockiego
12	Odrodzenia Radockiego – Odrodzenia Łętowskiego
13	Odrodzenia Łętowskiego – Odrodzenia Bażantów
14	Odrodzenia Bażantów – Odrodzenia Kościół
15	Odrodzenia Kościół – Odrodzenia Szewska

continue table 2.1

16	Odrodzenia Szewska – Piotrowice Osiedle
17	Piotrowice Osiedle – Ochojec Ziołowa
18	Ochojec Ziołowa – Ochojec Sadowa
19	Ochojec Sadowa – Ochojec Wapienna
20	Ochojec Wapienna – Brynów Kościuszki
21	Brynów Kościuszki – Brynów Dworska
22	Brynów Dworska – Brynów W. Pola
23	Brynów W. Pola – Katowice AWF
24	Katowice AWF – Katowice Mikołowska
25	Katowice Mikołowska – Katowice Mikołowska Sąd
26	Katowice Mikołowska Sąd – Katowice Dworzec

Source: Own work.

The travel parameters have been determined on the bases of the input date of Ride 1 and Ride 2. The zero, low, medium, and high speed ranges are defined. The zero speed pointers are set to 1 for speeds not exceeding 1 m/s (3.6 km/h). The low speed pointers are set to 1 for speeds above 1 m/s (3.6 km/h) and less or equal to 4 m/s (14.4 km/h), the medium speed pointers are set to 1 for speeds above 4 m/s (14.4 km/h) and less or equal to 10 m/s (36.0 km/h), and high speed pointers are set to 1 for speeds above 10 m/s (36.0 km/h). The bus speed is calculated at all track points. For each track point, on the basis of calculated speed, the value of speed pointers is determined. The assignment of track points to the individual speed ranges is presented in Table 2.2 for Ride 1 in off-peak hours, and in Table 2.3 for Ride 2 in peak hours.

Table 2.2

Assignment of track points to speed ranges for Ride 1

Section number j	Track Points N_j	Zero Speed Z_j	Low Speed L_j	Medium Speed M_j	High Speed H_j
1	292	70	144	78	0
2	226	93	54	79	0
3	117	18	15	34	50
4	268	95	30	77	66
5	117	31	10	50	26
6	131	75	26	30	0
7	223	79	52	65	27
8	214	51	105	58	0

continue table 2.2

9	68	17	8	43	0
10	103	33	18	52	0
11	294	171	25	91	7
12	57	13	8	21	15
13	55	15	7	24	9
14	63	13	8	16	26
15	79	20	7	22	30
16	136	60	24	39	13
17	65	14	9	42	0
18	100	26	7	67	0
19	112	36	15	40	21
20	269	141	35	51	42
21	185	51	34	72	28
22	189	42	29	65	53
23	113	18	25	14	56
24	127	58	24	45	0
25	119	37	18	52	12
26	213	69	123	21	0

Source: Own work.

Table 2.3

Assignment of track points to speed ranges for Ride 2

Section number j	Track Points N_j	Zero Speed Z_j	Low Speed L_j	Medium Speed M_j	High Speed H_j
1	352	88	190	74	0
2	167	38	61	67	1
3	124	27	12	25	60
4	287	46	62	177	2
5	120	37	12	43	28
6	65	16	21	25	3
7	798	501	246	51	0
8	374	215	95	64	0
9	58	14	7	19	18
10	92	23	16	53	0
11	127	22	18	51	36
12	67	22	6	34	5

continue table 2.3

13	84	42	7	35	0
14	66	17	6	14	29
15	73	15	7	24	27
16	155	58	46	40	11
17	76	22	9	38	7
18	98	21	16	52	9
19	87	23	6	27	31
20	231	109	36	36	50
21	190	44	25	117	4
22	143	16	10	48	69
23	147	17	35	54	41
24	85	15	24	46	0
25	208	69	78	61	0
26	290	162	100	28	0

Source: Own work.

The location data at the consecutive track points are recorded with a constant interval of 1 second, and thus the sum of the track points assigned to the individual speed ranges corresponds to the time in which the bus drives with the speeds included in those ranges.

2.6. Analysis of travel parameters

For analysis of travel parameters, data for the individual sections and for the entire consider bus route are used. The aggregated data for the entire bus route obtained in Ride 1 in off-peak hours and in Ride 2 in peak hours are presented in Table 2.4.

Table 2.4

Travel time with assignment to speed ranges

Ride	Travel time N (s)	Zero Speed Z (s)	Low Speed L (s)	Medium Speed M (s)	High Speed H (s)
Ride 1	3935	1346	860	1248	481
Ride 2	4564	1679	1151	1303	431

Source: Own work.

For Ride 1 in off-peak hours, the travel time for the entire bus route is 3935 s (about 1 h 6 min) and consists of a zero speed time of 1346 s (about 22 min), a low speed time of 860 s (about 14 min), a medium speed time of 1248 s (about 21 min), and a high speed time of 481 s (about 8 min). In pick hours, Ride 2 lasted longer and is 4564 s (about 1 h 16 min) consisting of a zero speed time of 1679 s (about 28 min), a low speed time of 1151 s (about 19 min), a medium speed time of 1303 s (about 22 min), and a high speed time of 431 s (about 7 min).

In peak hours the travel time for the entire bus route increased by 10 min which is about 15%. The increase of the travel time concerns the time assigned to the zero speed range and the low speed range while the changes of the travel time assigned to the medium speed range and the high speed range are minor.

2.6. Conclusion

The energy consumption of electric buses depends on travel parameters including driving time and speed profiles during the movement along the bus route. Analysis of travel parameters enables estimation of the typical energy consumption on the considered bus route. The considered bus route is divided into section according to location of bus stops along the bus route. The travel parameters at the consecutive track points of the bus route are determined on the basis of GPS data. Assignment of determined speeds to the defined speed ranges and their analysis allows assessment of the suitability of the considered bus route for operation with electric buses. Measurements in off-peak hours and in peak hours make it possible to take into account the impact of prevailing ambient traffic conditions on the travel parameters of the considered bus route. For bus routes located in mountainous areas, the division of speeds into speed ranges can be supplemented by elevation parameters, which allow consideration of impact of variable height.

DOI:10.34918/87423

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3. RISK ANALYSIS FOR USERS OF URBAN ROAD TUNNELS

3.1. Introduction

Urban road tunnels play an increasing role in the urban transport network. Until recently, tunnels facilitated communication mainly in mountain regions. Currently, they are more and more often built in cities and are used to organize transit traffic and run under densely built-up areas. Urban tunnels can also improve river crossing by connecting parts of the city separated by it. Transferring the city traffic to the tunnel allows for reorganizing the urban space, making it more inhabitants-friendly. Thus, since modern cities cannot do without traffic, and it is even expected to intensify, it should be at least partially hidden underground.

Safety considerations are also important as the serious risks to tunnel users are directly related to the nature of the tunnels. These threats are mainly caused by limited space, difficult access and difficulties in evacuation. Additionally, the nature of the road traffic must be taken into account, the main feature of which is a large number of independent drivers and passengers. Their behavior and detailed decisions, although governed by traffic regulations, are generally unpredictable.

Road incidents in road tunnels are less frequent than in other parts of the transport network because the tunnel itself calms the traffic[3]. There are no intersections in the

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Lu J.J., Xing Y., Wang C., Cai X.: Risk factors affecting the severity of traffic accidents at Shanghai river-crossing tunnel, Traffic Injury Prevention, 2015, Vol. 17, No. 2, pp. 176–180.

tunnels, no pedestrians, often speed limits are applied, and the influence of weather conditions is negligible. All of this moderates traffic and reduces the likelihood of an accident. However, if an accident does occur, its consequences are more severe than elsewhere[4].

Many road tunnel systems ensure the comfort of use and the safety of users, but the worst situation in which an accident occurs and, above all, a fire breaks out, cannot be ruled out. Then not only the people directly involved in the accident are at risk, but also all people in the tunnel. Even if a fire is not fully developed, a large part of the tunnel is filled with toxic and hot fire gases. The smoke reduces visibility and causes confusion. It also contains poisonous components that can quickly cause unconsciousness[5]. This zone, dangerous for human health and life, is growing rapidly, and in a few minutes it covers subsequent parts of the tunnel[6]. Therefore, it is extremely important that people trapped in the tunnel undertake self-evacuation in the initial stage of fire development. For this to happen, all tunnel safety systems must operate properly and support self-rescue[7].

When a fire breaks out in a road tunnel, the tasks of the safety systems include fire detection, precise locating, announcing a fire alarm, closing the tunnel entrance and switching the ventilation system to fire mode[8]. Currently, the basic element of the fire detection system is usually a fibro-laser sensor, which is a line detector spanning the entire length of the tunnel. Such a sensor detects either a temperature rise above a certain threshold or an unusual rate of temperature rise[9]. The reaction time of fire detection

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systems should not exceed 60 s[10], but there are reports in the literature of cases where a fire developed latently for several minutes and the detection took place only after a few minutes[11].

As urban road traffic is characterized by high traffic density and frequent congestion, a large number of people can be expected to be at risk in the case of a fire in the urban road tunnel. Estimating this number and examining the course of the evacuation is a very complex task, because the actual evacuation experiment in the conditions of even a simulated fire is very dangerous for its participants. For this reason, as a rule, only partial experiments are carried out on selected aspects of the considered issues. For example, evacuation experiments are conducted in artificial smoke or darkened rooms[12]. High costs and organizational difficulties make it impossible to freely study many real configurations of the fire development process in a road tunnel, hence it seems natural to use numerical simulations to investigate this problem.

Actually, it consists of three sub-problems:

Depending on the traffic intensity a number of vehicles move through a tunnel. It is possible that a congestion has been formed just due to the specifics of the urban traffic.

At a moment an accident or a vehicle malfunction happens and the fire outbreaks, then the fire is developing. Eventually all vehicles are forced to stop.

After some time the fire is detected and the fire alarm is triggered, the tunnel entrance is closed and the evacuation begins.

As it can be seen, there are quite different phenomena, which should be taken into account to model reliably the entire sequence of events: road traffic simulation, fire development simulation and evacuation simulation.

3.2. Research description

The coupled numerical research was proposed to cope with this problem. Three different software packages were used sequentially to solve the sub-problems, as is shown in Figure 3.1. There are lots of simulation tools available, but after an inquiry

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three of them were selected. The results reliability and the relative ease of semi-automatic data processing (which was important for coupling) were into account. The commercial software VISSIM has been chosen for modeling of traffic jam formation[13]. The commonly used FDS (Fire Dynamic Simulator) program[14] was applied to model the fire development and the smoke spread. The evacuation modeling PATHFINDER program[15] was used to track the escape routes of evacuees and to check their touch with harming factors.

The input data for traffic modeling concerning the generic traffic structure were adopted according to the General Traffic Measurement carried out by the Polish General Directorate for National Roads and Motorways in 2015[16]. The assumed fire powers corresponded to typical vehicle fires referred in the literature – they ranged from about 4-6 MW for a passenger car to 70 NW for a HGV with a flammable load[17]. The typical bus fire gives about 24 MW. The vehicles manning was generated randomly to fit the average values obtained in real measurements[18]. The movement speed of the evacuees was described by the normal distribution, which accounted for different fitness of people[19]. It was assumed that direct eye-witnesses of the accident started to escape first, the others had to wait for emergency announcement[20].

As an outcome PATHFINDER provides files with an individual history of each evacuee. Hence there are data on location of each person and conditions at this position available second by second. It allows for determination whether a person was in any touch with harmful factors (somebody was exposed) or the harmful influence exceeded the allowed dose (somebody was endangered)[21]. Hence, the final results of each run of the coupled numerical simulations was the number of exposed or endangered persons.

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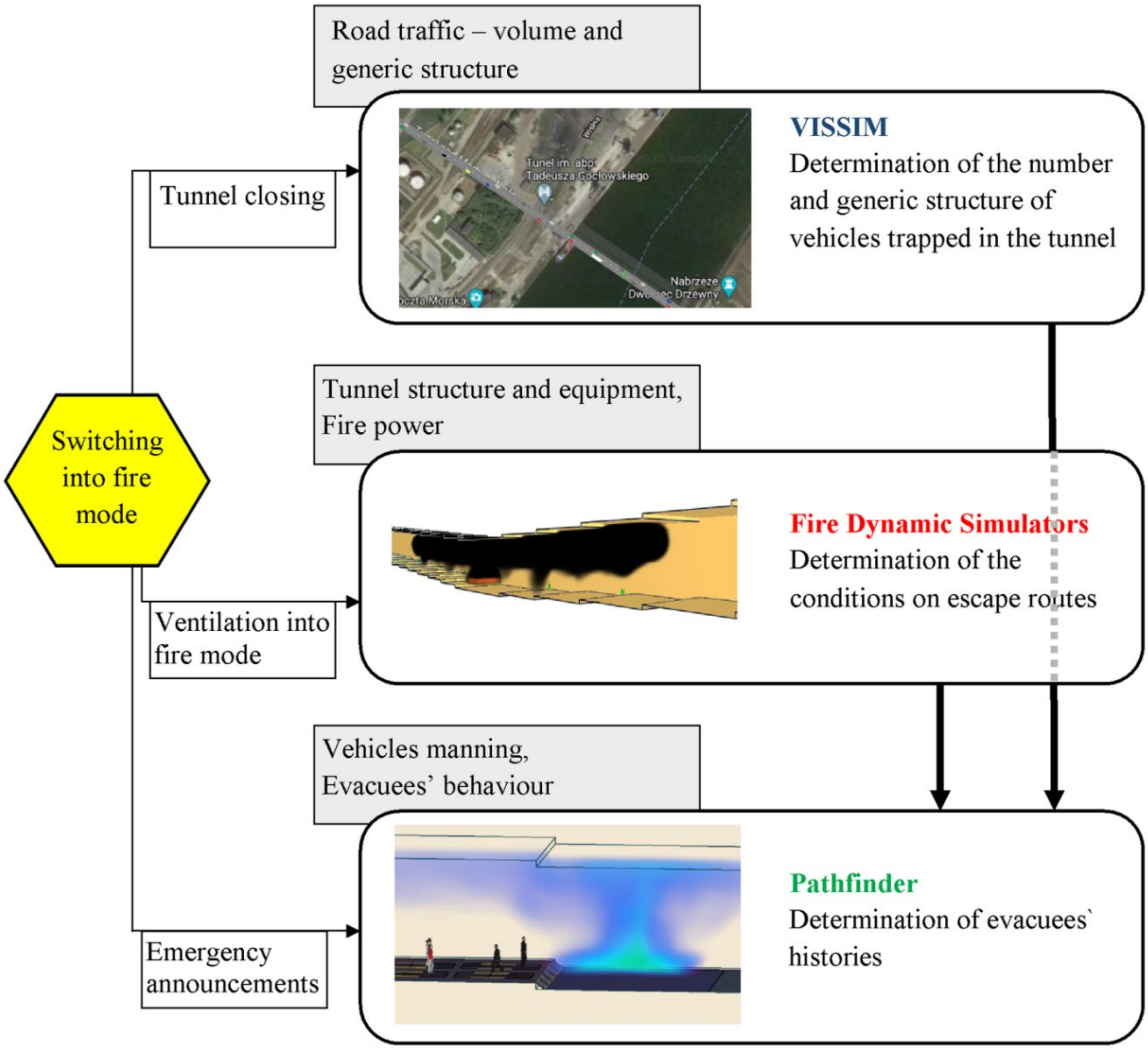

Fig. 3.1. Dataflow diagram of the coupled numerical simulations
Rys. 3.1. Schemat przepływu danych sprzężonych symulacji numerycznych
Source: Król A., Król M.: Numerical investigation on fire accident and evacuation in a urban tunnel for different traffic conditions. Tunnelling and Underground Space Technology, 2021, Vol. 109, 103751.

3.3. Results

The research was carried out in two stages. First, the general influence of different factors on the number of threatened people during a tunnel fire was examined, next a number of fire scenarios were studied for a selected real road tunnel.

A model of a typical tunnel was used in the first stage of the research. It was 680 m long and contained two lanes[22]. It was equipped with longitudinal or semi-transverse ventilation system: two axial fans were optionally supported by a number of fresh air supply vents, which were located just above the road surface (Fig. 3.2). In such system smoke was removed through one of the tunnel portals, the direction of fans' operation was generally in accordance with natural flow in the tunnel. In the semi-transverse configuration the vents supplied certain amounts of fresh air, which prevented the lowering of the smoke layer. The capacity of each fan was assumed as 20 m^3/s and the capacity of each vent was 1.5 m^3/s.

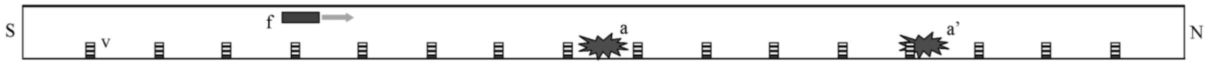

Fig. 3.2. The tunnel model (S and N – portals, f – axial fans, v – air supply vent, a and a' – alternative fire locations).
Rys. 3.2. Model tunelu (S i N – portale, f – wentylatory osiowe, v – otwory napowietrzające, a i a' – alternatywne lokalizacje pożaru.
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

Even simplified analysis would require considering lots of possible configurations of a fire accident and reactions of tunnel systems. Hence, after a preliminary selection 6 variables were taken into account. Since each of them can take a number of states the Taguchi method of experiment design was used to cope with this issue. It was assumed that each factor took two values. Table 3.1 shows the considered factors and their values.

Table 3.1

The examined factors and their values

No	Factor	Acronym	Value 1	Value 2
1	Fire detection time	DT	60 s	120 s
2	Fire location	FL	in the middle	150 m from S portal
3	Ventilation system	VS	longitudinal	semi-transverse
4	Traffic mode	TM	uni-directional	bi-directional
5	Traffic conditions	LS	free traffic	congested
6	Fire power	FP	6 MW	24MW

Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

[22] Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

Since there were 6 factors taking 2 values, the numerical experiment was carried out according to scheme described by L8 orthogonal table. Due to random nature of the road traffic there were 6 simulations runs of VISSIM applied for each series, then the results were averaged. The detailed review of the results revealed that the main harmful factor was the smoke. The influence of the high temperature was negligible and it was limited to the narrow zone in the close vicinity of the fire. Therefore it might concern just the passengers of the vehicles directly involved in the fire event. Meanwhile the smoke was spreading very quickly and after a relatively short time was able to obscure people far from the fire. The logical scheme of the experiment and the results are shown in Table 3.2.

Table 3.2

The results of the first stage

Series	DT	FL	VS	TM	LS	FP	Total	Exposed	Endagered
1	1	1	1	1	1	1	74±33	5±8	0
2	1	1	1	2	2	2	275±53	79±36	22±14
3	1	2	2	1	1	2	81±30	11±4	0
4	1	2	2	2	2	1	246±63	2±1	1±0
5	2	1	2	1	2	1	231±44	53±30	4±8
6	2	1	2	2	1	2	102±41	76±32	15±4
7	2	2	1	1	2	2	260±38	83±27	31±19
8	2	2	1	2	1	1	116±32	55±43	9±8

Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

As it can be seen the values differ significantly from one another, which proves the importance of analyzed factors. A relatively high value of standard deviation suggest also the values are scattered for each series. It resulted mainly from the random structure of the formed congestion. Especially high numbers of exposed or endangered people were caused by the presence of a bus or buses among trapped vehicles. The presented values were further processed according to the Taguchi idea: they were averaged for every factor and for every level to find out the individual contribution of the factors. The results are shown in Figures 3.3 and 3.4 – for each factor the left point corresponds to value no 1, the right one to value no 2.

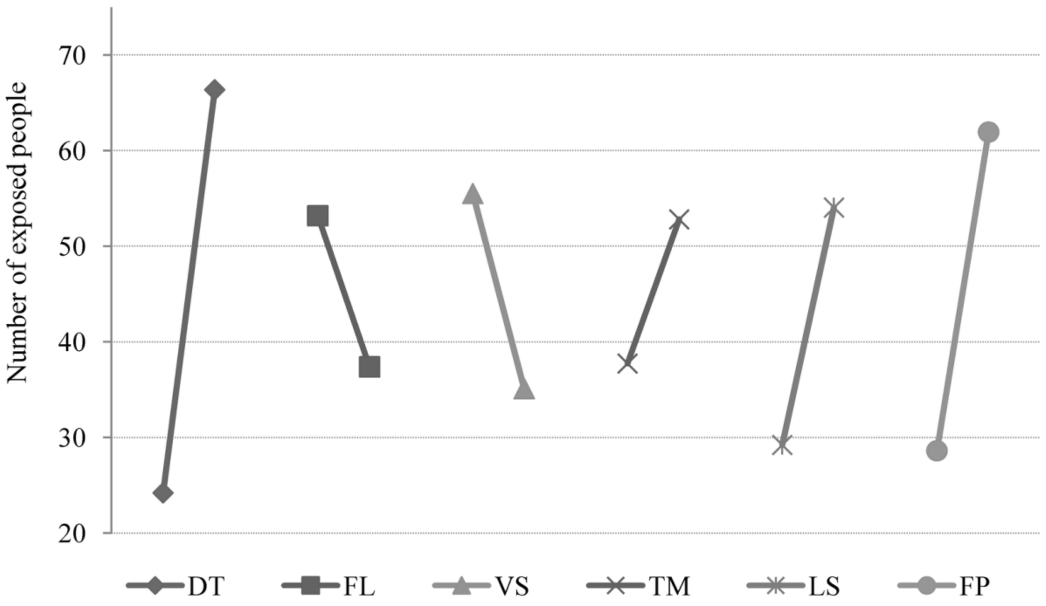

Fig. 3.3. Impact of the examined factors on the number of exposed people
Rys. 3.3. Wpływ badanych czynników na liczbę ludzi narażonych
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

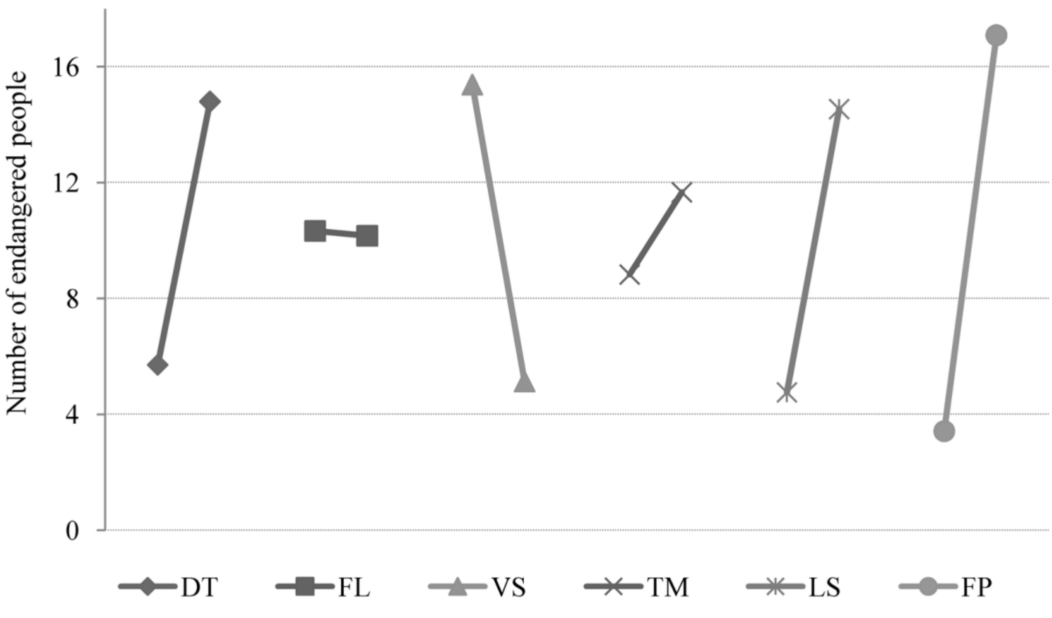

Fig. 3.4. Impact of the examined factors on the number of endangered people
Rys. 3.4. Wpływ badanych czynników na liczbę ludzi zagrożonych
Source: Król A., Król M.: The factors determining the number of the endangered people in a case of fire in a road tunnel. Fire Safety Journal, 2020, Vol. 111, 102942.

Although the values are different, both figures lead to almost the same conclusions. The most important factors are the fire power and the detection time. When just the number of exposed people is considered the detection time prevails, because the quick detection allows most people to avoid any touch with the harmful influence. According to the expectations the traffic intensity is important as well – simply for more intense traffic more people has been trapped inside the tunnel. A bit astonishing is the significant impact of ventilation system applied – the semi-transverse ventilation system is required by regulations only for tunnels longer than 3000 m, meanwhile if applied it drastically decreases the number of endangered people even for a relatively short tunnel. It was because the supplied fresh air kept a larger space free of smoke and thus allowed the evacuees to avoid any touch with it.

At the second stage of the research a number of fire scenarios was considered for a real urban tunnel. The analysis were carried out for the road tunnel located in Gdansk (Poland). It goes under the Vistula river from North-West towards South-East and connects the downtown with the harbor zone. It consists of two tubes of length of 1378 m with two lanes for each tube. The tube cross-section is 7.03 m high and 10.09 m wide. The vertical profile of the tunnel is v-shaped, the longitudinal inclinations are 3% for NW part and 4% for SE part and the deepest point lies 33 m under the river surface. Each tube is equipped with semi-transverse ventilation system, which consists of 11 axial fans placed every 95 m and 22 air supply vents. The thrust of axial fans is 1200 N in the normal direction and 407 N in the reversed mode.

The analysis involved three factors: fire detection time, fire power and traffic state. The fire was assumed to be located at the deepest point, just in the middle of the tunnel. Since it was shown previously that low fire power doesn't usually pose a big threat to the people in tunnel just high and very high fire powers were considered. The detailed list of examined cases is presented in Table 3.3.

Table 3.3

Cases being examined

Code	Fire detection time (s)	Traffic state	Fire power (MW)
ACE	60	Free	29
ACF	60	Free	70
ADE	60	Congested	29
ADF	60	Congested	70
BCE	120	Free	29
BCF	120	Free	70
BDE	120	Congested	29
BDF	120	Congested	70

Source: Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

The data on the road traffic concerning its generic structure, intensity and vehicles speed were obtained from tunnel supervising system and were shared for the research by Road and Greenery Management (ZDiZ) Gdansk. As previously six VISSIM simulation were carried out for each case, which allowed for accounting for the random nature of the road traffic. The results in form of the average number of endangered people are shown in Figure 3.5.

Just at first glance one can see, that there are three clear groups. The first group contains cases (ACE, BCE, ACF, ADE) with rather small number of exposed people. This corresponds to favorable accident conditions: lower fire power, quick fire detection or non-congested traffic. For the second group (BDE, ADF, BCF) the number of exposed people is about hundred. Here the impact of two threatening factors makes an unfavorable tangle. The third group consists of only one case (BDF), in which the coincidence of all danger factors have a disastrous influence and results in a huge number of threatened people.

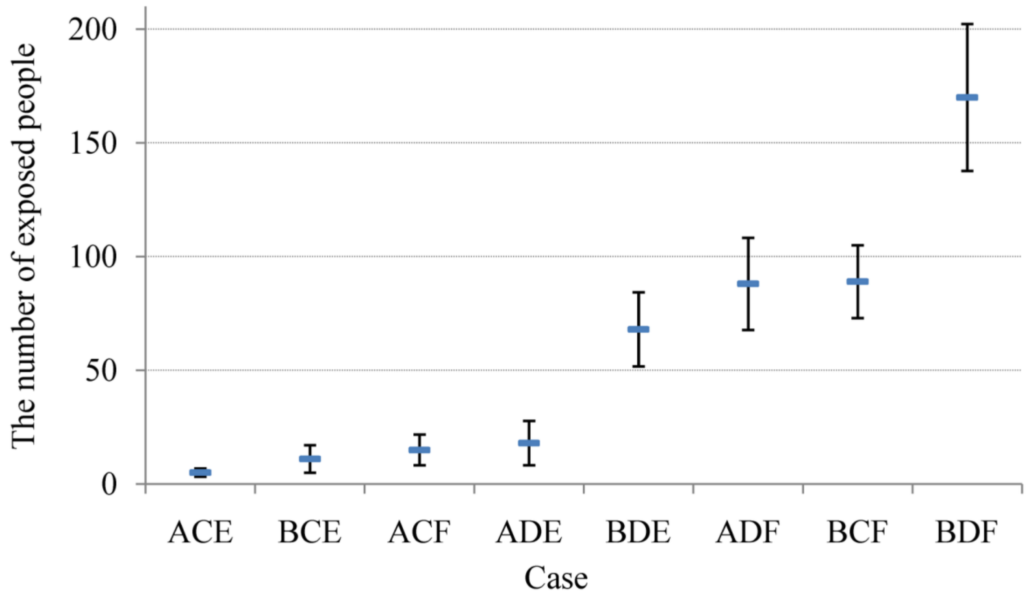

Fig. 3.5. The average number of exposed people for all cases
Rys. 3.5. Średnia liczba ludzi narażonych dla wszystkich przypadków
Source: Król A., Król M.: Study on hot gases flow in case of fire in a road tunnel, Energies 11 (13), 2018, pp. 1–16.

3.4. Conclusions

In large modern cities, traffic is often routed through tunnels. This solution is beneficial to the quality of urban space, but brings specific risks. The chapter presents the numerical research on the safety level of users in urban road tunnels during a fire outbreak. The novelty of the work is to apply the coupled numerical simulation for reliable modeling the entire process. First road traffic simulator VISSIM was used to model the congestion formation, then FDS software modeled the fire development and smoke spread and finally PATHFINDER provided the results in the form of individual histories of all evacuees. This allowed for finding the impact of the selected factors on the number of exposed and endangered people.

Although the results significantly fluctuated due to the random nature of road traffic a number of clear conclusions can be stated:

- A delayed fire detection resulted in an increased number of exposed people – time is the main factor during the evacuation.
- Smoke is the most danger factor – it is spreading quickly and affects people even far from the fire event.
- For congested traffic the number of exposed people may be very high, however just few of them are in a real danger.
- Very high power fires are especially danger because in such cases large amounts of smoke are produced.
- If unfavorable circumstances are entangled the number of endangered people may be very high.
- The fire location in the tunnel is of minor importance.
- If a bus or a number of buses are involved in a fire accident the number of threatened people significantly increases – it is due to the prolonged time needed to leave the bus.

Since the time factor appeared to be crucial, the ability to self-evacuate efficiently plays the most important role in the initial stage of the fire. This requires at least basic knowledge on proper evacuation procedures[23].

[23] Schmidt-Polończyk, N., Wąs, J., & Porzycki, J. (2021). What is the knowledge of evacuation procedures in road tunnels? survey results of users in Poland. Buildings, 11(4), 146.

DOI:10.34918/87424

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4. JUST CITY. MODERN MOBILITY IN THE CONTEXT OF CREATING JUST CITIES

4.1. Introduction

The chapter deals with modern means of mobility in the context of creating just cities. The issue was taken up in the belief that in the era of VUCA (volatility, uncertainty, complexity, ambiguity)[2] the priority should be to take all measures aimed at creating urban justice, which can be realized, among others, through modern mobility – which the Author tries to prove.

Adopted research theses:

- Modern mobility is a condition for building good accessibility for different social groups to important areas and objects of the city.
- Good transport accessibility is a condition of a just city.
- The introduction of modern mobility systems to the existing spatial structures of the city may be a means to their reconstruction, modernization, revitalization and making them more attractive.

The concept of a just city was based on an understanding of justice defined as "equality before the law, equality of opportunity or equality of accessibility"[3]. In order to explain the connection of urban justice with urban planning and mobility, the theoretical part of the paper discusses selected ideas of city planning. It is shown that their postulates to improve the quality of life of inhabitants, link justice with transport accessibility and appropriate spatial planning. The main objective of this research is to recognize the influence of modern mobility on the creation of an just city, to demonstrate

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[2] Rose J.F.P.: Dobrze nastrojone miasto. Karakter, Kraków 2019, p. 27.

[3] Karwińska A.: Miasto sprawiedliwe. Idee i możliwości realizowania. „Prakseologia" nr 156/2014, Instytut Filozofii i Socjologii Polskiej Akademii Nauk / Akademia Leona Koźmińskiego, Warszawa 2014, p. 79–106.

the dependence of the existence of an just city on accessibility, and the existence of accessibility on the selection and operation of mobility types. The focus is also on formulating concrete conclusions to the theory of urban planning and design practice.

The topics of the work include the elucidation of the concept of the just city and the analysis of the influence of mobility on the formation of accessible spaces within its framework. The scope includes public transport issues in medium-sized cities.

The research methods used in the chapter include: a case study based on the author's criteria, an analysis of the situation of the public transportation system in a selected city (Gliwice), the author's analysis of the distribution of urban zones in the city (Gliwice), and the preparation of concepts for the reconstruction of the public transportation system and architectural-urban concepts for selected parts of the city in the context of public spaces (as a Project Based Learning method).

4.2. Just city

4.2.1. Ideas of city planning- state of the art

The earliest idea of city planning, which has been the foundation for later assumptions, is the ideal city. The broad concept of the "ideal city" can be understood in various ways – due to the fact that concepts based on the "ideal" shaping of cities were developed in different historical epochs, and therefore reflected a different hierarchy of values depending on the era – but above all, they were to strive to meet the needs of people. As Zbigniew Paszkowski notes[4] "the ideal city is understood as a certain challenge to create an ideal environment for people to live. This environment should meet the needs of a single individual (person, inhabitant), as well as the collective forming a particular community".

As one stage in the development of the ideas of city planning, the concept of the smart city emerged, which prioritizes the basic postulates of the idea of sustainable development in the processes of design and adaptation of cities[5]. It defines six areas of a smart city – smart economy, smart environment, smart people, smart living conditions,

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[4] Paszkowski Z.: Miasto idealne w perspektywie europejskiej i jego związki z urbanistyką współczesną. Wydawnictwo Universitas, Kraków 2011, p. 20.

[5] Wach-Kloskowska M., Rześny-Cieplińska J.: Inteligentny i zrównoważony rozwój transportu jako element realizacji założeń koncepcji smart city – przykłady polskie i europejskie. Studia Miejskie, t. 30, 2018.

smart governance and smart mobility[6], which, according to experts, is one of the most important drivers to improve the quality of life of citizens[5]. Intelligent mobility is understood as innovative and integrated transport systems using energy from renewable sources, as well as the spatial and functional integration of the public transport system through the creation of elements linking different types of mobility: transfer hubs, park&ride and bike&ride hubs, intelligent transport systems, passenger information systems, compatible and synchronized timetables[7] and uniform transport fares. By reducing exhaust emissions, noise, travel time and chances of congestion, and above all by using modern means of transport, the accessibility of city space and comfort of living in it increases.

Another concept discussed in the work is the compact city[8], which calls for the creation of dense, intensively and multifunctional used living spaces that implement the principles of sustainable development, served by efficient, multimodal public transport systems (in combination with walking and cycling – "while reducing the need for individual car transport"[8]). Examples of the implementation of the idea of a compact city are the concepts of a 15-minute or 1-minute city[9].

Also cited is the concept of the happy city[10] in which the aspect of equity, mobility and accessibility to urban goods is explicitly emphasized. It calls for the city to offer "real freedom to live, move around and shape our lives as we see fit as well as a "fair and equitable distribution of space, available services and mobility to its inhabitants"[10].

In conclusion, the synthesis of the aspirations, demands and goals of the mentioned ideas is a just city, which is based on comprehensive, equal and socially just assumptions based on accessibility and equality of opportunities, which can be realized, among others, through modern mobility.

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[6] Giffinger R., Fertner C., Kramar H., Kalasek R.: Smart cities: Ranking of European medium-sized cities. Centre of Regional Science (SRF), Vienna University of Technology, Vienna 2007.

[7]Gadziński J., Goras E. (eds.): Raport o stanie polskich miast. Transport i mobilność miejska. Instytut Rozwoju Miast i Regionów, Warszawa 2019.

[8] Mierzejewska L.: Miasto zwarte, rozproszone, zrównoważone. Studia Miejskie, t. 9/2015, p. 14-15; Neuman M.: The Compact City Fallacy. Journal of Planning Education and Research, 2005, Vol. 25, No. 1, p. 14.; Węcławowicz-Bilska E.: Miasto przyszłości – tendencje, koncepcje, realizacje. Czasopismo Techniczne. Architektura, z. 1, 2012, p. 328; Polit A.: Idea miasta zwartego a rzeczywistość. Czasopismo Techniczne. Architektura, z. 14, 2010, p. 88; Stangel M.: Kształtowanie współczesnych obszarów miejskich w kontekście zrównoważonego rozwoju. Wydawnictwo Politechniki Śląskiej, Gliwice 2013; OECD. Compact City Policies: a Comparative Assessment. OECD Green Growth Studies, OECD Publishing, 2012, p. 15; Sepioł J. (ed.): Przestrzeń życia Polaków. Warszawa 2014; Ogrodnik K.: Idea miasta zwartego – definicja, główne założenia, aktualne praktyk. ARCHITECTURAE et ARTIBUS t. 4/2015, p. 15; Ministerstwo Infrastruktury i Rozwoju: Krajowa Polityka Miejska 2023. Warszawa 2015.

[9] O'Sullivan F.: Make Way for the 'One-Minute City'. Bloomberg CityLab, 2021. Available online: www.bloomberg.com/news/features/2021-01-05/a-tiny-twist-on-street-design-the-one-minute-city [accessed on April 2021].

[10] Montgomery Ch.: Miasto szczęśliwe. Jak zmienić nasze życie, zmieniając nasze miasta. Wydawnictwo Wysoki Zamek, Kraków 2015.

4.2.2. Accessibility

Special attention is given to accessibility formulated through access to social life, resources of the city, all necessary (most public) services and fulfillment of basic needs, regardless of an individual's capabilities, life situation, financial and intellectual resources. One of the most important factors realizing the aforementioned “accessibilities” is transport accessibility that provides all inhabitants with equal opportunities to participate in social and professional life. These needs can be met through mobility (specified in the city planning concepts discussed in the work). Mobility that is realized by intelligent, modern and integrated transport systems makes it possible to create a just city.

Accessibility is also defined in the research as the design of spaces, transport stops or means of transport according to the principles of universal design[11], which state that they should be designed and adapted in an inclusive way for all users, ensuring equality and opportunities to use urban goods and social life in a non-stigmatizing way.

4.2.3. Relation to priority research areas of the Silesian University of Technology, POB4: Smart Cities and Future Mobility

The research under discussions in line with the activities undertaken by the Silesian University of Technology under Priority Research Area 4 (POB4), focusing on Smart Cities and Future Mobility. One of the main sub-areas of research is technological and spatial development to meet identified needs, overcome contemporary constraints, improve the efficiency of solutions, and reduce the negative impacts of the expansion of human activities on the environment and human quality of life. The following issues were cited as topics for POB4[12]:

- development of means of road and off-road transport, with special emphasis on environment-friendly and performance-improving solutions,
- developing collective public transport systems available to different passenger groups, with particular regard to the persons of special needs and limited mobility.

[11]Benek I., Labus A., Kampka M. (ed.) – Fundacja Laboratorium Architektury 60+: Wytyczne w zakresie projektowania uniwersalnego mając na uwadze potrzeby osób niepełnosprawnych. Ekspertyza wykonana na zlecenie Ministerstwa Infrastruktury i Budownictwa, Warszawa 2016.

[12] Sierpiński G. (ed.): Priorytetowy Obszar Badawczy 4: Inteligentne miasta i mobilność przyszłości. Gliwice 2021, Available online: www.polsl.pl/pob4/en/research-topics/ [accessed on May 2022].

4.3. Characterization and analysis of modern means of mobility

Five modern modes of transportation were selected for analysis in the research portion of the work. The selection was dictated by their characteristics related to range, capacity, location, innovation, and ownership type. For the case study, vehicles were selected that have local coverage and are collective or group, road and above-ground, modern and public.

4.3.1. Typology – criteria for evaluation of means of transport

In order to conduct a study of selected means of transport and to prove the thesis that modern means of transport can be an important factor in creating a just city, evaluation criteria were adopted. Aspects and factors affecting the city space and inhabitants were also taken into consideration.

Table 4.1

Criteria for evaluation of means of transport

No.	SPATIAL	
1.	Spatialabsorptivity	
	spatial- -devouring	Means of transport that require the use of a large amount of urban space, and the introduction of which requires significant transformation of the spatial tissue (demolition, redevelopment, actions significantly changing the cityscape)
	intrusive into spatial issue	requiring changes in the city's structure (in infrastructure spaces or public spaces), slight reconstructions and transformations to a small but visible extent
	spatial-saving	making use of the existing layout and structure of the city, not requiring significant transformations of the urban tissue, not generating spatial conflicts or collisions with the existing types of mobility.
2.	Type of spaceimpact	
	agresive	dominating the space, due to their size, amount, way of moving, appearance, way of functioning in the urban mobility system, taking away the possibility of democratic use of urban space
	neutral	non-interfering with the city tissue, not requiring significant amounts of space for functioning, not causing congestion, not bringing disharmony to the spatial and visual order
	friendly	integrated into the city's structure, interacting with existing urban mobility systems and extending their functionality and efficiency, supporting the democratisation of the use of urban space

continue table 4.1

FUNCTIONAL		
3.	flexible	able to respond and adapt to changing user needs
4.	reliable	not subject to congestion, meeting the needs of users, enabling easy, fast and convenient travel, accessible in time and space, giving access to other means of mobility within a wider multimodal system
FORMAL		
5.	Enhancing valours	positively influencing the attractiveness of the city in terms of: aesthetic and visual, convenience and comfort, investment, competitiveness and accessibility
6.	transport stops	evaluation of the form of transport stops in terms of their accessibility (based on universal design principles), functionality and spatial aspects. The analyses also pay attention to the development of the space in the immediate vicinity of the stops
ECOLOGICAL		
7.	with environmental impact	emitting harmful substances to the environment, having a large ecological footprint, requiring the use of non-organic and non-recyclable materials, threatening blue and green infrastructure
8.	Without environmental impact	environmentally neutral, made of sustainably sourced and recyclable materials, with no harmful emissions, using renewable energy sources, promoting (or at least not threatening) blue and green infrastructure
9.	Environmentally friendly	meeting the requirements described above and additionally supporting sustainable urban development, plus-energy: producing more energy than they use, cleaning the air, etc.
SOCIAL		
10.	Accessibility	
	Decreasing accessibility	reinforcing or contributing to “urban sprawl”, strengthening transport exclusion (not only the means of transport themselves, but also their organisation and use as an argument for creating inaccessible spaces), having a “monopoly” on the use of space, while reducing access to it for other users
	Increasing accessibility	supporting the “compactness” of the city, allowing to fight against transport exclusion, having the possibility to connect places without public transport connections (or with small number of such connections) with bigger centres/destinations, equalising opportunities, giving the possibility to meet basic needs

continue table 4.1

11.	Universality	
	inaccessible, exclusive	not meeting the principles of universal design, generating spatial barriers, not dedicated to all users - the use depends on physical and intellectual abilities, financial resources; perpetuating social differences
	accessible, inclusive	which can be used by everyone, fulfilling the principles of universal design, meeting the needs of many user groups, not excluding anyone, not generating spatial barriers, democratic and inclusive, enabling everyone to move freely to the same extent, inexpensive or free, ensuring freedom and independence, not perpetuating social differences, intended for everyone
12.	safe	in the literal sense and in the sense of security

Source: Own elaboration based on the research question.

4.3.2. Selected modern means of mobility

The following modern transportation means were selected for analysis using the case study method and for evaluation according to the adopted criteria. Below is a summary of the scores (scale 1 to 5) given to the means of transport analysed in the case study – to be interpreted in accordance with the description of the criteria detailed in section 4.1.

Table 4.2

TEB-1

No.	Criteria	Rating	Description
1.	SPATIAL		
	Spatial absorptivity	3	Introducing it into the complex and heterogeneous space of the city is impossible. All the roads on which TEB-1 would travel would have to be exactly the same width, plus there would be a need to create additional lanes for regular buses, trucks and other taller vehicles. In practice, it is impossible not to interfere with the existing infrastructure and to avoid major reconstruction.
	Type of space impact	1	Due to its size, TEB-1 is heavily dominant in space. Its operation is aggressive – the organisation of traffic in the city would have to be subordinated to its crossings – especially at intersections, when drivers of cars driving under the TEB-1 platform would want to make any manoeuvre. The form of a kind of tunnel, which gives the impression that it is 'pulling in' the other vehicles, would cause anxiety and discomfort to traffic participants.
2.	FUNCTIONAL		
	flexible	2	No high adaptability – low flexibility to adapt travel routes to changing user needs in terms of line routing and destinations – requires road adjustments.
	reliable	4	The main strength of the TEB-1 concept is its reliability – adapted to move over traffic, it cannot be blocked by a traffic jam and should therefore always arrive on time. It increases travel convenience and reduces travel time.

continue table 4.1

3.	FORMAL		
	Enhancing valours	3	The announcements of the introduction of TEB-1 into Qinhuangdao City's transport system has resulted in increased investment potential and an increased number of contracts awarded for the construction of new infrastructure – making the city more attractive and competitive.
	transport stops	2	The bus stop has not been designed according to the principles of universal design in any respect, which excludes many user groups. The form of the bus stop itself is visually intrusive and can negatively affect the perception of the space.
4.	ECOLOGICAL		
	environmental impact	3	The planned electric propulsion system, if the announced alternative energy sources (photovoltaic panels) are used, has a neutral impact on the environment (excluding the production process of the panels themselves from the assessment). There is no information on the recyclability of used batteries or on the origin of the materials from which the vehicle is made.
5.	SOCIAL		
	Accessibility	3	TEB-1 travel routes must be straight-line (only forward and backward movement possible), which would only work well for a rapid transit line, for example between the centres of neighbouring cities, or for shorter intra-urban distances, which would not increase accessibility or create urban compactness, only the speed of travel.
	Universality	3	There is a lack of information about the adaptation of platforms for people with different dysfunctions. Because of its limited mobility within the urban structure, it does not remove transport exclusion or add value to social equalisation. A means of transport that is easy to use, uncomplicated and usable by everyone.
	Safety	1	TEB-1, through its tunnel-like, enclosed form, generates many dangers and opportunities for collisions. Drivers of vehicles underneath the bus have no view of their surroundings and no knowledge of what is happening on the road outside its structure. Also dangerous are the very attempts to manoeuvre when passing under the TEB-1, with all junctions, exits and turns becoming even more collision-prone. Driving under the bus platform, as well as the arrival of the bus and the car driver suddenly finding themselves in an enclosed tunnel, generates disorientation, anxiety and unpredictable behaviour.
average rating:		**2,4**	

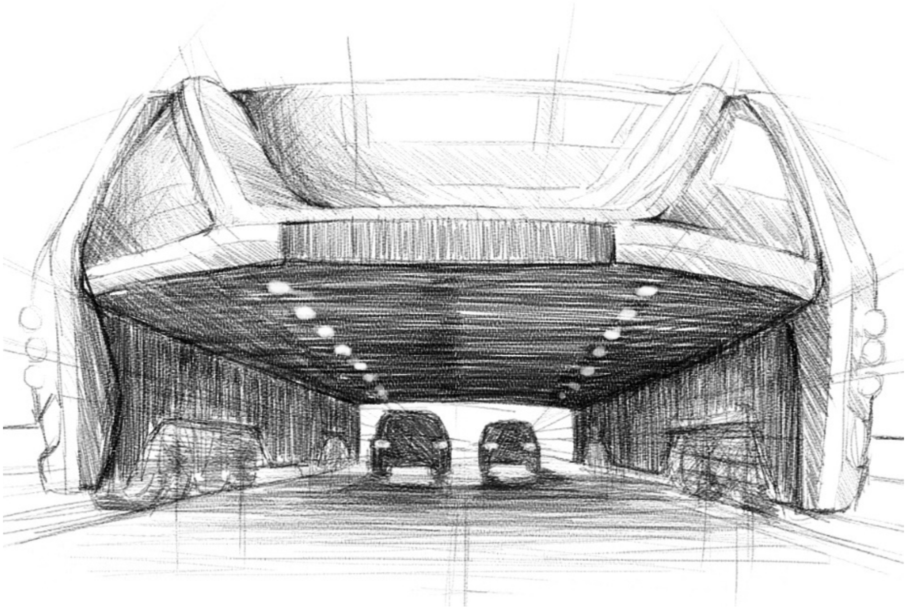

Fig. 4.1. TEB-1
Rys. 4.1. TEB-1
Source: Own elaboration based on: www.transport-publiczny.pl/wiadomosci/chiny-pamietacie-autobus-pod-ktorym-przejezdzaja-auta-zbudowali-go-52659.html, [access on 07.05.2022].

Table 4.3

Skyway

No.	Criteria	Rating	Description
1.	SPATIAL		
	Spatial absorptivity	3	It does not require a significant amount of urban space to be developed exclusively for its operation – the movement of the cabins takes place above ground, so no significant transformation of the urban structure is needed – SkyWay uses and fits into the existing layout. It can use the undeveloped space above the roads and other undeveloped tracts without significant interference.
	Type of space impact	4	SkyWay has the potential to develop the functionality and efficiency of existing transport systems – it can be a new, additional link to extend the capacity and efficiency of a city's multimodal systems. The form of the vehicles themselves is not overwhelming, giving the impression of being light and friendly.
2.	FUNCTIONAL		
	flexible	4	It is possible to adapt routes to meet the changing needs of users in terms of line routing and destinations. It is also possible to expand the cabins with further modules to meet the increased demand for passenger volumes. The designed timetable-free continuous transit system can automatically adjust the frequency of the carriages (in real time) thanks to artificial intelligence, increasing the efficiency of the city's transport system. Traffic tracks must be routed in a straight line, which limits the flexibility of routing.
	reliable	5	SkyWay is being designed primarily to make travel reliable and comfortable – the concept is to make travel independent of traffic and worsening congestion.

continue table 4.3

3.	FORMAL		
	Enhancing valours	4	It can have a positive impact on the city's attractiveness, especially in terms of accessibility, competitiveness (in terms of innovation, convenience of travel and living comfort) and can thus enhance the city's investment appeal, positively influencing development.
	transport stops	4	The architecture of interchanges can be adapted to the qualities of a specific location. Due to their size and the amount of space required (open spaces around the facility) they cannot, however, be used in spaces with limited space, but located, for example, in suburban areas they can have "place-making" potential – provide an opportunity to create attractive locations for interpersonal integration and a variety of functions that can increase the potential of a place. It is possible to design bus stops in the trend of universal design.
4.	ECOLOGICAL		
	environmental impact	3	The planned electric propulsion, if alternative energy sources (photovoltaic panels) are used, has a neutral impact on the environment (excluding the production process of the panels themselves from the assessment). Information is given on the use of a very small amount of raw materials and materials to create all the infrastructure dedicated to SkyWay, compared to the creation of infrastructure for other modes of transport. Its construction and location do not interfere with existing ecosystems, green areas.
5.	SOCIAL		
	Accessibility	5	It has great potential to combat transport exclusion. Due to its low implementation costs and the ease of adapting the line's routing to transport needs, SkyWay has the potential to connect places without public transport links to larger centres, thus having a positive impact on generating accessibility and urban compactness.
	Universality	3	The need to board cabs at high interchange stations creates a spatial barrier, but on the other hand, stops can be adapted to the needs of all user groups. By being able to adapt the route to mobility needs, it has the potential to bridge transport exclusion, thus bringing new opportunities for social equalisation. A means of transport that is easy to use, uncomplicated and can be used by everyone.
	Safety	4	By elevating the rail structure above the ground, the possibility of collisions with other traffic participants is eliminated. With regard to the feeling of safety, the fear of heights, probably determined by the overall glazing of the cabs, may be a problem.
average rating:		**3,9**	

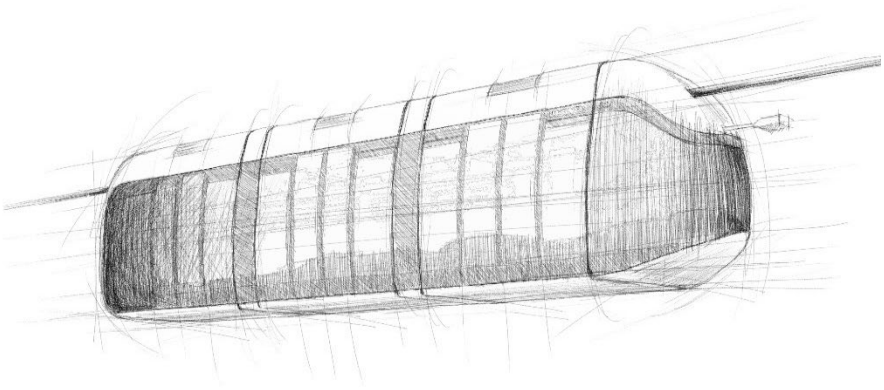

Fig. 4.2. Skyway
Rys. 4.2. Skyway
Source: Own elaboration based on: www.skyway.capital/technology [access on 07.05.2022].

Table 4.4

Cable car

No.	Criteria	Rating	Description
1.	SPATIAL		
	Spatial absorptivity	3	The most space is required for the location of interchange stations needing significant space horizontally and vertically. Support structures for cable systems take up relatively little space near the ground. The routing of the routes can, however, depend on the layout and height of the buildings. This results not so much in interference with the urban fabric itself, but in the need for an often complex (and in many locations impossible) adjustment to it.
	Type of space impact	3	The interchange stations themselves can take on attractive forms that are consistent with their surroundings. Carriages or gondolas can be personalised to suit the needs of a particular city. On the other hand, it can be quite aggressive for the cable system and moving cabs to take over the “sky space”, introducing new, alien elements. This can cause discomfort and anxiety.
2.	FUNCTIONAL		
	flexible	4	Cable cars routes can be established in locations inaccessible to conventional modes of transport and despite spatial barriers such as tracks, motorways, rivers, etc., so in open spaces route flexibility is at a high level. In denser urban areas, routing depends on spatial considerations. Timetables, frequency and number of cabs can be adapted to user demand dynamically, responding in real time.
	reliable	5	Because of their complete independence from traffic, conditions, rush hour or congestion, cable cars are reliable. Breakdowns are very rare, and if there is a power outage, for example, it is possible to bring the cabins manually to the station. They offer the possibility of effectively complementing a city's existing multimodal systems.

continue table 4.4

3.	FORMAL		
	Enhancing valours	5	Thanks to their advantages, they significantly increase the attractiveness of the city in terms of quality of life, access to goods and investment and tourism. They increase the city's development potential and help promote it.
	transport stops	4	It is in the hands of architects to design the stations – they can take any form, can be adapted to local conditions and locate boarding points at pavement level. Stations have place-making potential (placemaking) which would encourage the development of local centres and attractive public spaces.
4.	ECOLOGICAL		
	environmental impact	4	Cable cars use electric propulsion, so (assuming it comes from clean sources) they do not emit harmful substances into the environment. They have few breakdowns and do not require frequent maintenance. Stations can be equipped with photovoltaic farms to generate the required energy in a sustainable way. They do not pollute the air or emit noise. Far fewer raw materials are needed to build the routes than for conventional modes of transport.
5.	SOCIAL		
	Accessibility	5	They increase accessibility to jobs, education, services, commerce, healthcare and the whole range of cultural and social assets of the city. Due to their flexibility, they are able to connect remote, hard-to-reach neighbourhoods with other locations, increasing opportunities and equality for residents. They have the potential to bridge transport exclusion.
	Universality	4	The use of cable cars is open to everyone, regardless of fitness, age or financial resources. Station buildings and cabins are adapted to the needs of people with disabilities, they are boarded from floor level and have adapted spaces for wheelchairs, bicycles, prams, luggage or bicycles. A means of transport that is easy to use, uncomplicated and can be used by anyone.
	Safety	4	Due to the separation from traffic, there is no possibility of any collisions, accidents or crashes. Some people may experience anxiety due to heights or open space, and (from a position on the ground) anxiety due to cabs moving overhead.
average rating:		**4,1**	

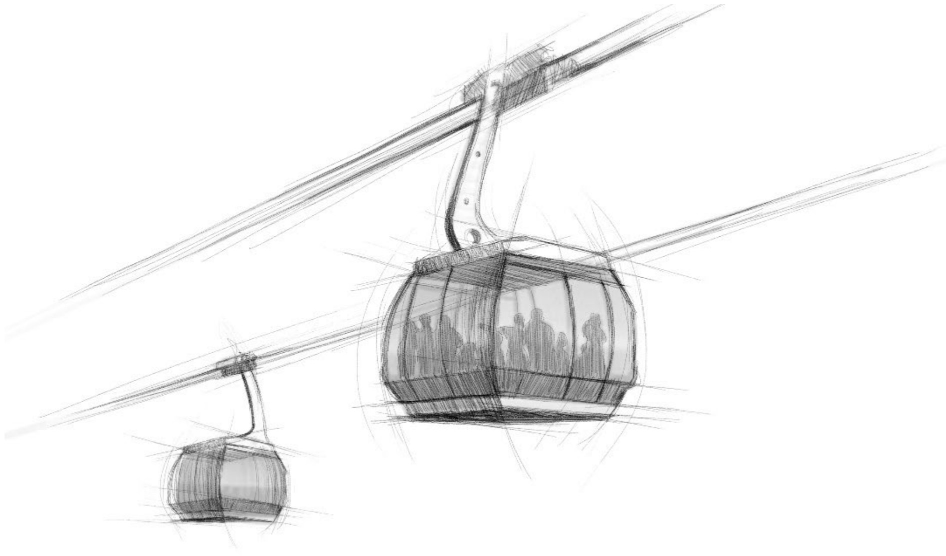

Fig. 4.3. Cable car
Rys. 4.3. Cable car
Source: Own elaboration based on: www.hollywoodreporter.com/lifestyle/lifestyle-news/la-mayor-eric-garcetti-proposes-gondola-dodger-stadium-1106141/ [access on 07.05.2022].

- Personal Rapid Transit – PRT

Table 4.5

Personal Rapid Transit – PRT

No.	Criteria	Rating	Description
1.	SPATIAL		
	Spatial absorptivity	4	They are not as space-consuming as road infrastructure for cars or buses, however they do require a certain amount of space to be adapted to their needs. Routes could be located on a similar basis to tramways. The routing of routes within the city structure must depend on spatial considerations and the amount of space available.
	Type of space impact	5	Depending on how the track is run (above ground, elevated or overhead) the nature of the impact on space would be different. Above-ground tracks would be the least aggressive, and would not stand out too much visually, as might be the case with elevated or suspended systems. The vehicles themselves are small, giving the impression of being friendly, not overwhelming.
2.	FUNCTIONAL		
	flexible	5	Already at the level of the idea, the system can be considered highly flexible, dynamically adapting to the situation and responding to changes in demand. Arrival times and routes are individually tailored to circumstances. Due to the need to build dedicated tracks for the PRT, the designation of the transport network is dependent on the existing structure of the city (width of traffic routes, amount of free space) and must conform to it.

continue table 4.5

	reliable	5	The PRT is very reliable, not subject to major breakdowns that, for example, immobilise the entire system for an extended period. Highly efficient and personalised journeys and decoupling of movement from traffic and worsening congestion.
3.	FORMAL		
	Enhancing valours	5	The PRT can be a major competitor to individual modes of transport, thus providing an opportunity to change the mobility habits of city users and thus be a leaven for improving all aspects of urban living and commuting, which is attractive in terms of investment, development and increasing competitiveness against other centres.
	transport stops	5	Stops can take a variety of forms, from larger interchanges bringing together multiple vehicles to stand-alone, single-stop stops. The possibility to board vehicles directly from the pavement means that access to this mode of transport is not restricted to a narrow group of users and therefore does not exclude the elderly, people with disabilities or people with pushchairs.
4.	ECOLOGICAL		
	environmental impact	3	PRT uses electricity, which has no negative impact on the environment (if the energy is obtained from renewable sources). It does not pollute the air or emit noise. Far fewer raw materials are required for the construction of special routes than for conventional means of transport. Thanks to intelligent management systems, energy to power the vehicles is not wasted by unnecessary trips, so losses are reduced as much as possible.
5.	SOCIAL		
	Accessibility	4	They could successfully serve passengers from further away neighbourhoods (several kilometres), providing them with a fast connection to the city centre, other neighbourhoods or functional areas (workplaces, education centres, etc.). They could positively contribute to the accessibility and connectivity of the city.
	Universality	4	PRT vehicles are adapted to carry people with disabilities. The journeys are not costly and can be customised, increasing transport accessibility. The only problem may be service – you have to hail the vehicle in person and then choose the destination station yourself, which may be problematic for e.g. digitally excluded people.
	Safety	4	The system is almost accident-free. The routes are collision-free, separated from other means of transport and traffic participants. Thanks to central control and autonomy, the human factor is also eliminated. The sense of security may depend on the size of the cabins.
average rating:		**4,4**	

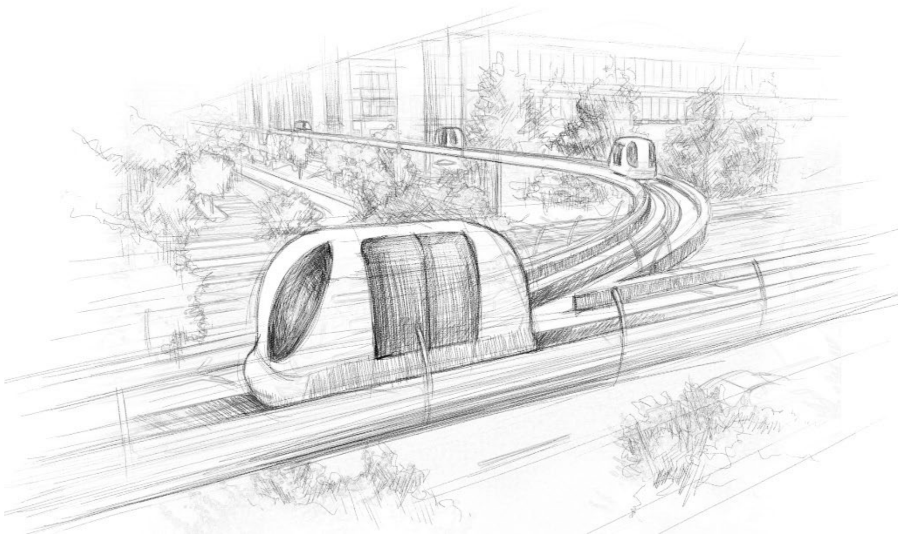

Fig. 4.4. Personal Rapid Transit
Rys. 4.4. Personal Rapid Transit
Source: Own elaboration based on: www.greenvillejournal.com/news/self-driving-pods-could-be-the-future-of-urban-transport-in-greenville/ [access on 07.05.2022].

Table 4.6

Shweeb

No.	Criteria	Rating	Description
1.	SPATIAL		
	Spatial absorptivity	4	The routes can be adapted to the existing structure of the city, they do not have to be straight, which helps to avoid spatial conflicts or forced line routes that are not adapted to the needs. There is no need to interfere with the existing fabric of the city – Shweeb uses the existing shape of the space and fits into it.
	Type of space impact	4	The capsules themselves are small in size, with transparent walls, so they do not overwhelm with their appearance. The tracks on which passengers move have a small cross-section, so they do not obstruct the view, the sky, or block access to light. Support structures may be a problem – due to the track span of 20 meters, the density of masts can be overwhelming.
2.	FUNCTIONAL		
	flexible	4	The line itself is very susceptible to changes and is easy to rebuild and modify. The lack of the need for a straight-line transport network allows for flexible adaptation to the existing urban structure, offering freedom in determining the route of the network connecting various destination points.
	reliable	3	With good organization and management, Shweeb has the potential to be reliable. However, it is questionable what will happen to the capsules from which the passenger will get off at the intermediate station – after all, the cabins are powered only by pedaling by the person inside, so it is not possible to automatically control the units from the central system.

continue table 4.6

3.	FORMAL		
	Enhancing valours	5	The introduction of the Shweeb system into the urban transport system would have a positive impact on the investment and tourist attractiveness of the city. It would also have a positive impact on the attractiveness of individual places that would use this method of traveling between slightly separated points.
	transport stops	2	The stops must be raised above the level of the sidewalk due to the technological solutions of vehicle drive. Taking into account the exclusionary nature of Shweeb (it is intended only for able--bodied people), its transfer stations can also be described in a similar way.
4.	ECOLOGICAL		
	environmental impact	4	The Shweeb is powered by muscle power by pedaling, like a bicycle. It uses no fuel or electricity. It is cheap to operate, and when designing the rails, the authors took into account the possibility of reusing the material when transport networks were to be dismantled, modified or liquidated. Shweeb could also be environmentally friendly, as it could itself produce energy generated by user traffic.
5.	SOCIAL		
	Accessibility	1	Due to the fact that the system requires significant expenditure of the user's physical strength, it is difficult to imagine that it would be possible to use it to travel, for example, from distant suburbs or to work in economic zones, which are most often far from city centers.
	Universality	1	Shweeb is not available to many user groups. To use this means of transport you must be physically fit, have a good level of fitness, and have standard body dimensions (all cabins are the same size, people who are overweight, very tall or very short might not be able to use this type of mobility), be well oriented in space and have good reflexes and skills in operating the cabin – the passenger himself has to switch to adjacent traffic lanes in order to change the route, which can be very discouraging. Due to its strongly urban character, Shweeb will not improve the accessibility of the city for people from places excluded from transport.
	Safety	2	Moving in the cabin is safe, and collisions with other road users are excluded by separating the movement space. However, the feeling of safety when driving a Shweeb may be low. A feeling of danger may be caused by situations when a passenger traveling at a higher speed catches up with the driver in front of him and “connects” the two capsules. This is done by a kind of impact and then by accelerating the movement of the slower passenger. Despite the installed shock absorbers, such an event can cause disorientation, fear and pressure to move at speeds beyond one's strength.
average rating:		**2,9**	

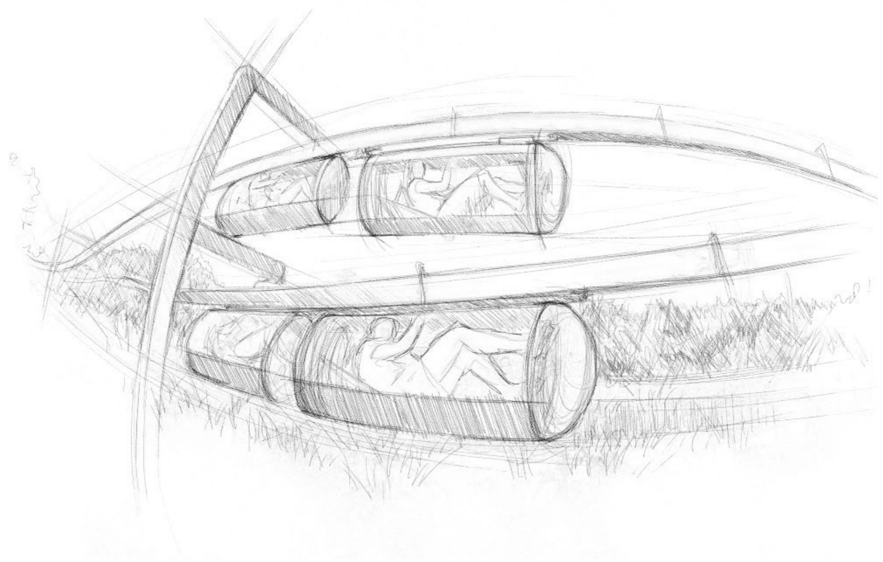

Fig. 4.5. Shweeb
Rys. 4.5. Shweeb
Source: Own elaboration based on: http://obviousmag.org/en/archives/2011/12/schweeb_revolution_skycyling_through_the_city.html [access on 07.05.2022].

The highest rated (average rating above 3,5) transportation means were selected for the conceptual section of the study: Skyway, cable car and Personal Rapid Transit.

4.3.3. Summary and conclusions of the analyses

The shared features of the highest rated transport means (Skyway, cable car, PRT) were:

- possibility of introduction without strong interference in the spatial structure;
- possibility of serving areas which are difficult to access by conventional means of transport;
- possibility to adapt to the needs of hygiene and sanitary safety;
- creation of new, efficient connections adapted to the needs of city users;
- zero-emission;
- collision-free, separated from the traffic of standard means of transport;
- dynamic adjustment of frequency to the needs of users, high flexibility in response to changes
- egalitarian;
- accessibility: stops/stations accessible from the sidewalk or adapted to people with special needs;
- place making potential.

4.4. Conceptual part

The conceptual part of the work proposes an optimal urban planning solution that involves increasing accessibility, streamlining and democratizing the space of selected urban areas and methods of movement. The concept was made atthree scales:

- Macro scale: includes solutions within the borders of a selected city (Gliwice), i.a. division into characterized spatial-functional zones and proposal of layout of the network of connections;
- Meso scale: includes a model of the network of connections and location of stops in selected fragments of the city's zones
- Micro/urban scale: solutions including fragments of public spaces which serve selected transportation stops of the proposed mobility means.

4.4.1. Selection of means of transport to the spatial-functional zones of the city

The recommendation for the selection of modern mobility for inclusion in the existing transport systems was based on the characteristics of the individual spatial-functional zones of the chosen city (Gliwice).

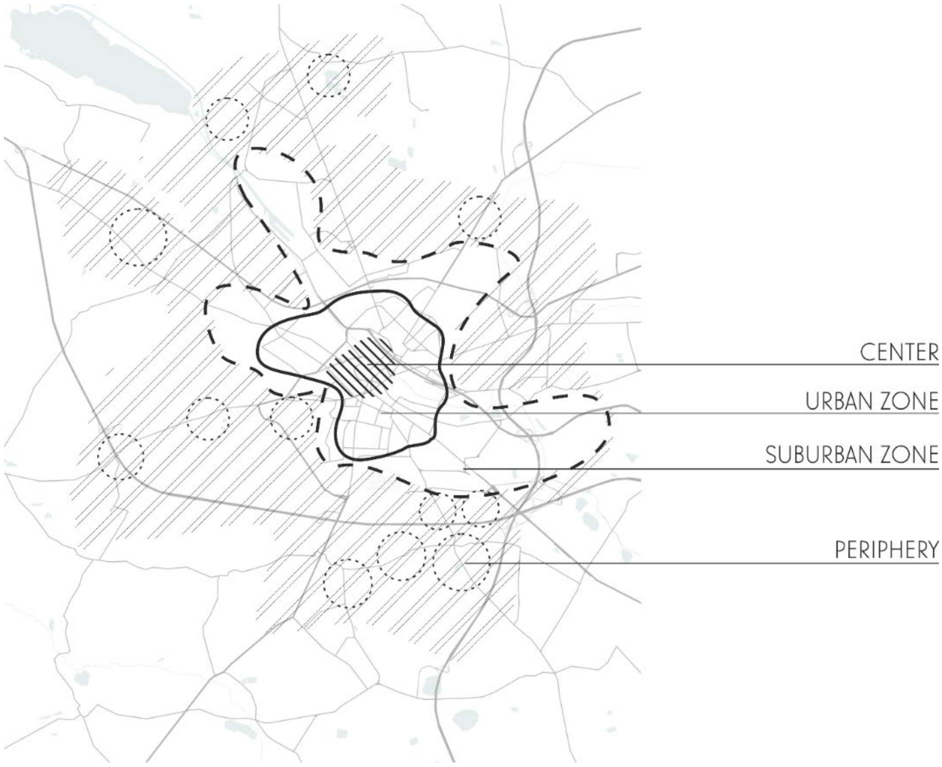

Fig. 4.6. Zoning of the city Gliwice
Rys. 4.6. Podział miasta Gliwice na strefy
Source: Own laboration.

The following zones were identified in analyses whose main criterion was the physical and spatial structure of the city: center (1), urban zone (2), suburban zone (3), periphery (4) – and then, on the basis of these characteristics, appropriate modern mobility measures were selected to meet the desired features for each zone.

Table 4.7

Recommended allocation of modern mobility measures to city zones

<table>
<tr><td>Zone</td><td>Desired characteristics of the means of transport</td><td rowspan="5">Traditionalmeans of transport +</td><td>Complementary means of transport</td></tr>
<tr><td>CENTER</td><td>fast and dynamic transit, short distance, on demand, spatial-saving</td><td>Personal Rapid Transit
Cablecar</td></tr>
<tr><td>URBAN ZONE</td><td>Fast transit, medium and long distance, frequent, on-demand or timetable-free, on fixed routes, low or mediumlevel of spatialabsorptivity</td><td>Personal Rapid Transit
Cable car
SkyWay</td></tr>
<tr><td>SUBURBAN ZONE</td><td>medium and long distance, frequent, running every 15/30 minutes on fixed routes, medium or higher level of spatial absorptivity</td><td>Cablecar
SkyWay</td></tr>
<tr><td>PERIPHERY</td><td>long distance, running according to needs, without timetables along fixed routes</td><td>SkyWay</td></tr>
</table>

Source: Own elaboration based on the research question.

The introduction of modern means of transportation into existing transportation systems should be based on the following aspects:

- dependence on local conditions and the spatial structure of the city, as well as the character of individual urban zones;
- complementing the existing means of transport and creating with them a complementary multimodal transport system as an interconnected, coherent network (in terms of routes, timetables, interchanges, unified ticketing system and e.g. the application supporting it)
- consistent wayfinding and visual identification;
- low fares or completely free public transport

4.4.2. Assumptions of the proposed model of communication systems and connection networks – macro scale

The proposed transportation model assumes that all zones of the city can be connected by supplementing existing transportation systems with modern means of mobility in a way that allows direct travel between zones and individual centers by identifying traffic generators. The model also seeks to increase the quality of intra-zone travel. Due to the character of the central zone, the aim is to reduce the amount of motorized traffic in it, so that pedestrians and cyclists take the lead. Transport interchanges are planned (e.g. typical interchanges connected with park-and-ride hubs) It is proposed to incorporate modern means of mobility into existing systems to address areas of need not met by traditional, commonly used means of transportation and to increase their efficiency and reliability.

A concept on a macro scale has been shown on Fig. 4.7.

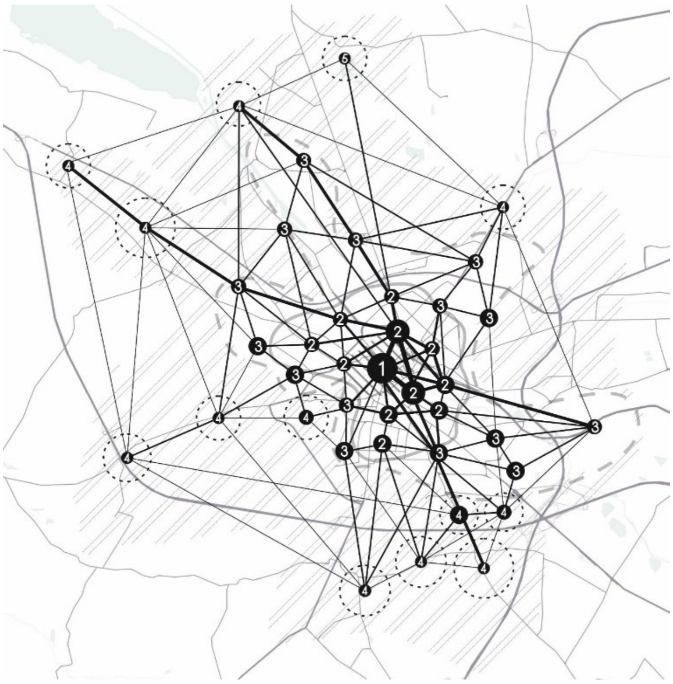

Fig. 4.7. Scheme of the proposed model of communication systems and connection networks in a sample city.[(1) – point-designated traffic generator in centre zone, (2) – in urban zone, (3) – in suburban zone, (4) – in periphery]

Rys. 4.7. Schemat proponowanego modelu systemów komunikacji i sieci połączeń w przykładowym mieście. [(1) – punktowo wyznaczony generator ruchu w strefie centrum, (2) – w strefie miejskiej, (3) – w strefie podmiejskiej, (4) – w strefie peryferiów]

Source: Own elaboration.

4.4.3. Conclusions and recommendations from the analyses, solution proposal, expected effects of introducing the proposed model – meso scale

The analytical section of the concept part characterizes the existing transportation system in the selected inter zone area, and examines local conditions in terms of transportation exclusion, mobility needs, travel purposes, and opportunities for deployment of the proposed mode of travel.

After summarizing the analyses, design guidelines are presented:

- complementing the existing transport system with modern means of mobility to complement its inadequate functioning;
- locating new stops in areas of "transportation white spots" devoid of access to public transportation;
- densifying the network of intra-zonal connections;
- increasing the frequency of services;
- creating a fast, long-distance line connecting the suburban zone directly with other zones
- increasing the competitiveness of public transportation in relation to individual car transport;
- introducing the aspect of multimodality and locating functional interchanges;
- increasing accessibility to urban goods for residents of all zones;
- increasing the attractiveness of undeveloped areas for investment purposes by running a high-speed transportation network through them.

Based on the conclusions and recommendations from the analyses, a model of a network of modern means of mobility and location of stops was proposed. Its main assumption is to complement the existing transportation system in order to eliminate "transportation white spots" and thus increase accessibility in meeting the basic needs of inhabitants from many social groups. The model was created for each mode of transportation:

A. Skyway – As a fast, almost direct connection between the suburban zone with the urban zone and the city center. Stops are located near important places such as a local center, a concentration of educational functions, or an interchange.

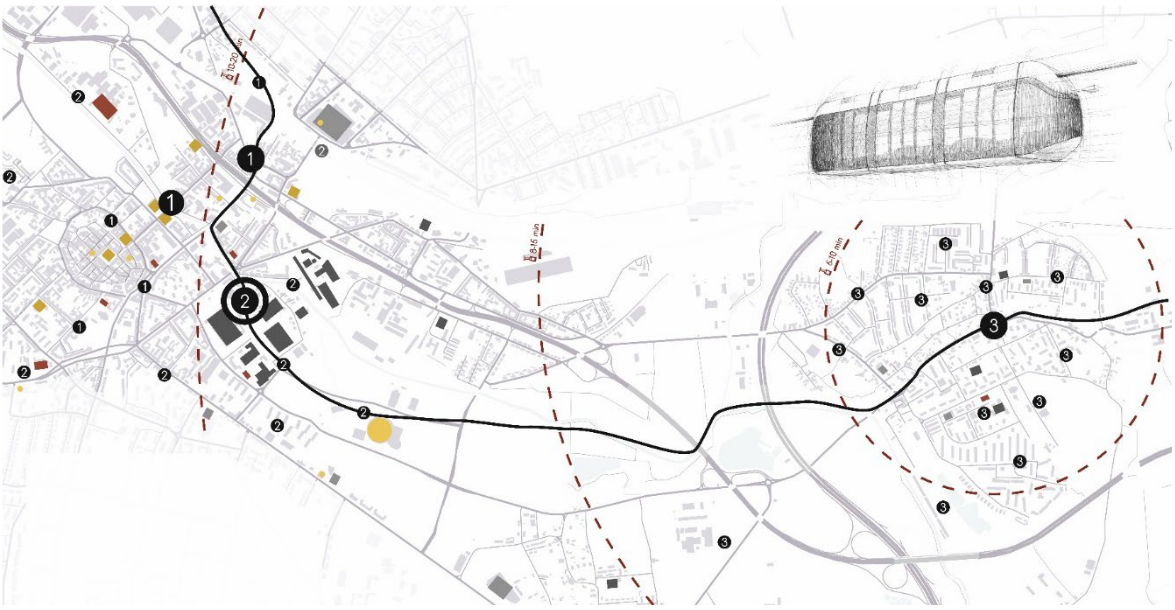

Fig. 4.8. Model of network and stops for Skyway
Rys. 4.8. Model sieci i przystanków dla Skyway
Source: Own elaboration.

B. Cablecar – increases accessibility to selected areas by filling in gaps in the existing transportation grid, connecting the most significant locations in a given zone.

Fig. 4.9. Model of network and stops for Cable car
Rys. 4.9. Model sieci i przystanków dla kolei linowych
Source: Own elaboration.

C. Personal Rapid Transit – a complementary, dynamic element of the transportation system in the center, which allows direct access from point A to point B – so it can compete with individual means of transport, and thus can relieve traffic congestion in the compact spaces of the central zone.

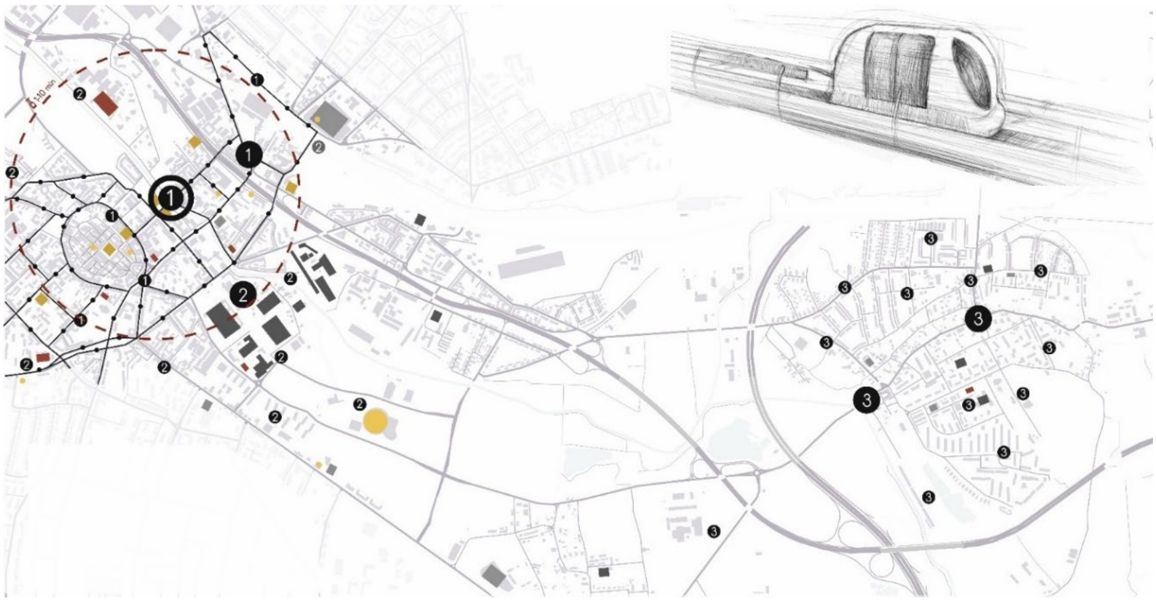

Fig. 4.10. Model of network and stops for PRT
Rys. 4.10. Model sieci i przystanków dla PRT
Source: Own elaboration.

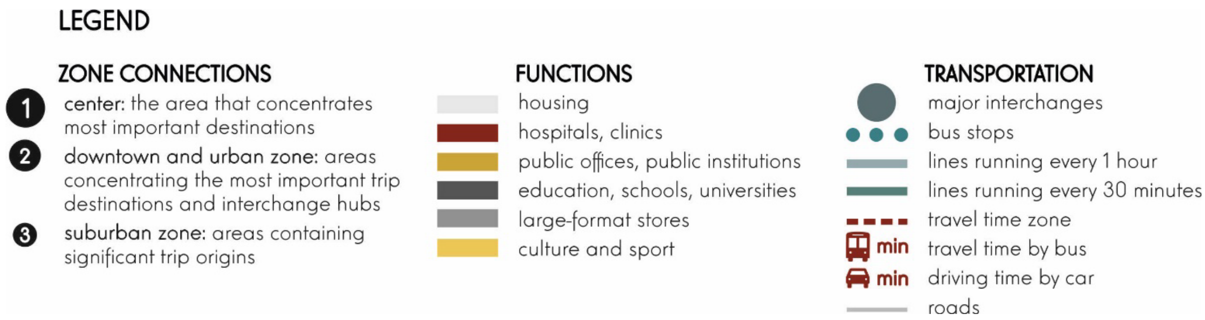

Fig. 4.11. Legend for network and stop models in meso-scale
Rys. 4.11. Legenda do modeli sieci i przystanków w skali mezo
Source: Own elaboration.

Desired outcomes of the proposed concept:

- increasing accessibility and urban justice by complementing the existing single--mode transportation system to eliminate transportation white spots that impede access to the use of the city's basic services and goods;
- a proposal to open a direct transportation line to the most important locations in the city center;
- creating the competitiveness of public transportation in relation to individual means of transport: shortening the time and increasing the speed of travel, decreasing the need for changes, and decreasing the distance of stops from the place of residence;
- individualized public transportation;
- transport system based on many different means of mobility – traditional and modern;
- place making – creating new multifunctional public spaces, including local centers;
- making undeveloped areas of the city more attractive for investment

4.4.4. Description of solutions in the urban concept – micro scale

For the conceptual design: the determinants of an accessible street identified in the article "Accessibility in the design of woonerfs in historic centers of European cities"[13] were taken into consideration, such as:

- "increasing safety,
- eliminating spatial barriers,
- clarity of space,

[13] Labus A., Malicka-Skrzek S., Gajewska A., Goleśna A., Jonda J., Konsek P., Ławecka A., Dostępność w projektowaniu woonerfów w historycznych centrach miast europejskich. Builder 2021, R. 25, No. 6, p. 64–68.

- increasing the amount of urban greenery,
- making it possible to spend time in the street space."

A. Center – green areas have been arranged, the form of which allows for the creation of places to sit, places for bicycle racks and urban furniture. Personal Rapid Transit traffic lanes in the central area have been separated from the pedestrian and bicycle zones by green spaces and a lines of trees. Pedestrians and cyclists have priority throughout the street, and thanks to the intelligent PRT system there are no collisions at pedestrian crossings.

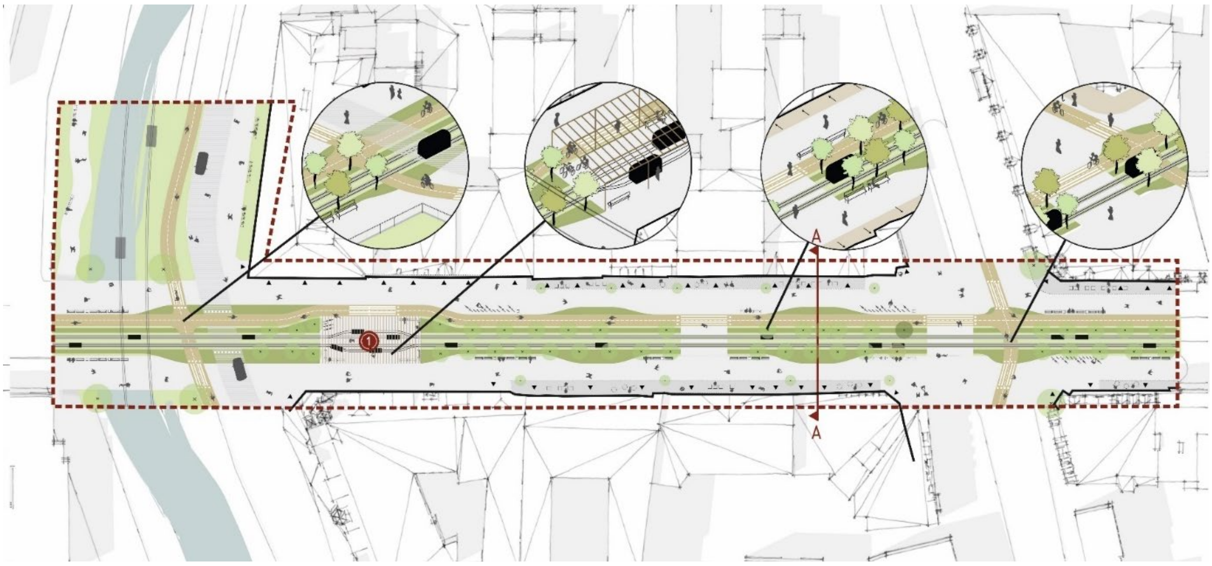

Fig. 4.12. A schematic concept of the center zone development
Rys. 4.12. Schemat koncepcji zagospodarowania terenu strefy centrum
Source: Own elaboration.

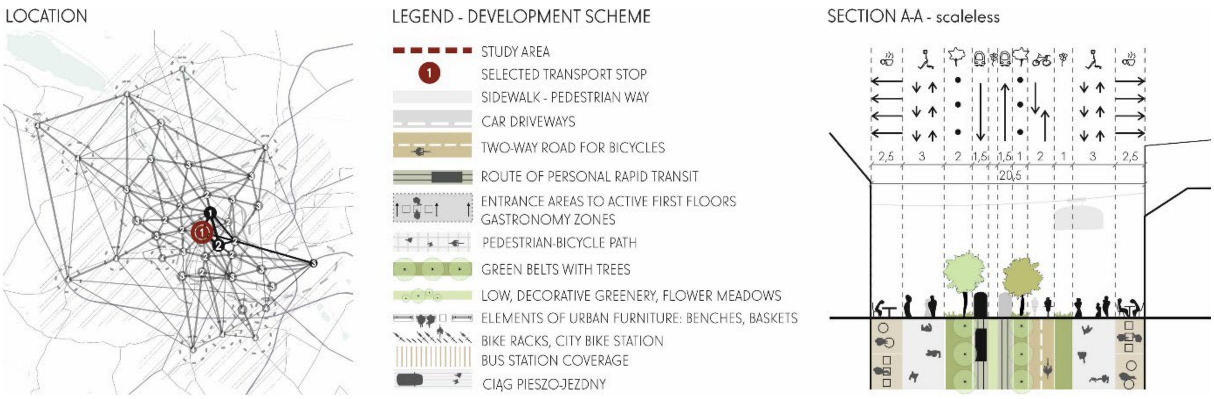

Fig. 4.13. Legend and site section for A schematic concept of the center zone development
Rys. 4.13. Legenda oraz przekrój terenu do schematu koncepcji zagospodarowania terenu strefy centrum
Source: Own elaboration.

B. Suburban zone - in the suburban zone there are located interchange stations for cable cars and SkyWay. Thanks to the proximity of the bus stop and city bike station a kind of multimodal transfer hub has been created. Pedestrian and bicycle space was designed as a woonerf with services and gastronomy. Spaces by the revitalised stream have been developed for recreational functions. Car lanes were narrowed to the minimum allowable widths to slow traffic and reclaim territory for pedestrians and cyclists.

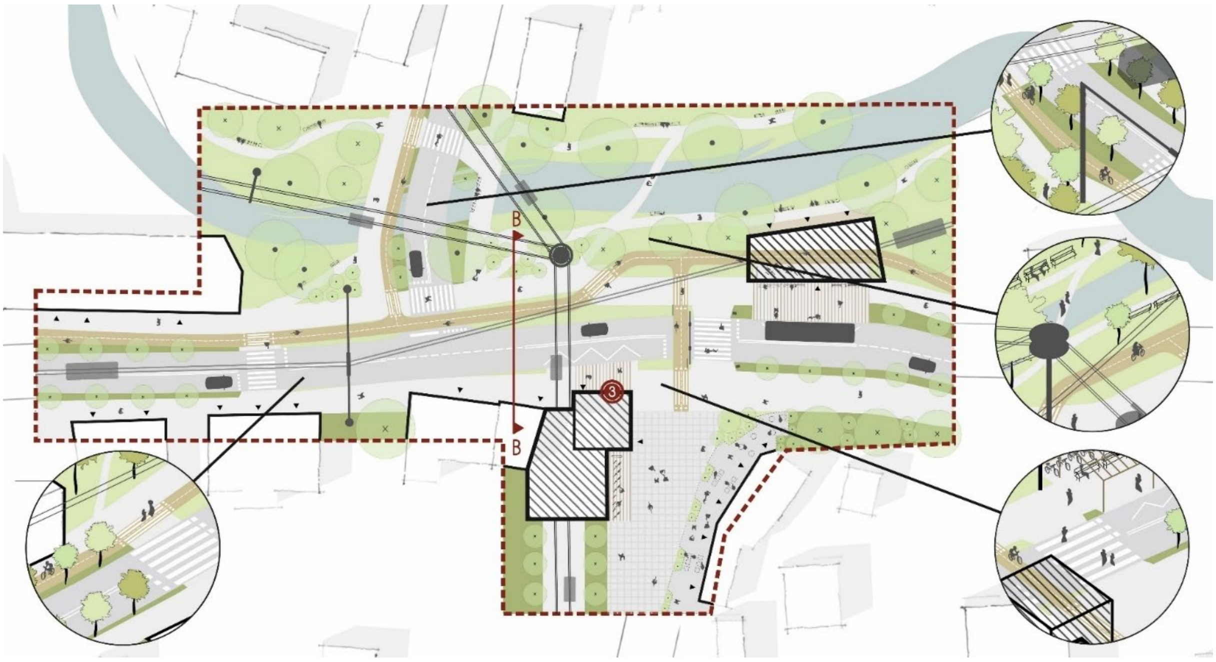

Fig. 4.14. A schematic concept of the suburban zone development
Rys. 4.14. Schemat koncepcji zagospodarowania terenu strefy podmiejskiej
Source: Own elaboration.

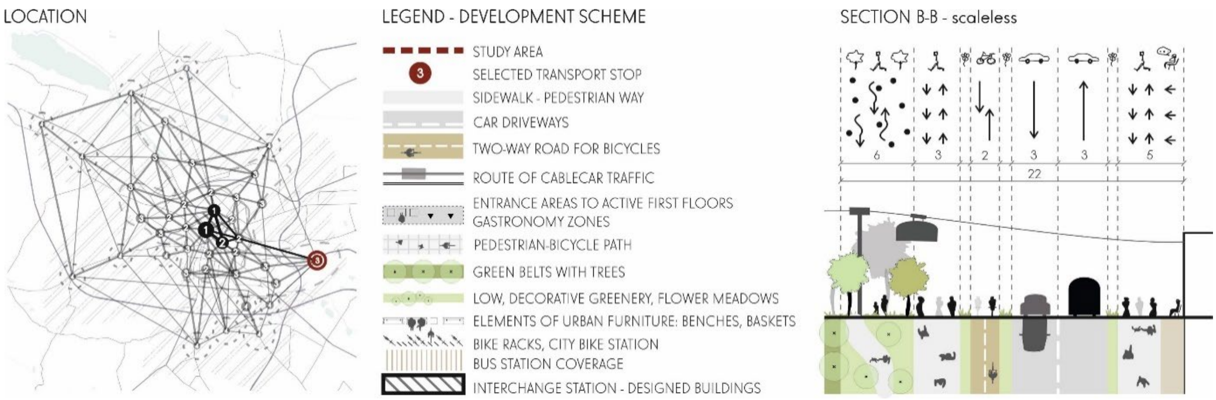

Fig. 4.15. Legend and site section for A schematic concept of the suburban zone development
Rys. 4.15. Legenda oraz przekrój terenu do schematu koncepcji zagospodarowania terenu strefy podmiejskiej
Source: Own elaboration.

4.5. Conclusions and summary

The final conclusions of the paper are that the analytical work points to the crucial importance of accessible public transport in the construction of a just city, the conceptual work points to the feasibility of such solutions that can respect the evaluation criteria adopted at the outset, and it is cosidered that the theoretical and conceptual work is worth continuing. Such continuation should be of an interdisciplinary nature, in which the participation of the architect and urban planner will be significant.

By reviewing selected relevant urban design ideas in terms of mobility issues and defining the just city, it can be concluded that accessible, efficient, safe, reliable, inclusive, complementary and multimodal modern public transport systems are the basis for creating accessible, just city spaces. They enable users to move freely, to improve their opportunities (through access to jobs, education), to have equal access to the services and goods of the city, to participate in social life and through their continuous development to improve the quality of life of their inhabitants. The proper selection of criteria in the implementation of modern means of mobility creates the possibility of sustainable city development.

DOI:10.34918/87425

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5. ANALYSIS OF PUBLIC TRANSPORT ACCESSIBILITY – A CASE STUDY OF TYSIĄCLECIA GÓRNE ESTATE IN KATOWICE, POLAND

5.1. Introduction

Smart cities are the cities open to the problems of their inhabitants. The main subject of these part of manuscript is the analysis of public transport accessibility within selected estate of Poland. The aim of this chapter is to draw attention to the problems of residents of selected areas related to transport accessibility, as well as to present the selected method of collecting data and analysing the situation. The chapter does not concern sociological analyses, but focuses on problems with movement, in particular of parents with small children, the elderly and the disabled.

Accessibility of public transport has been the subject of an increasing number of studies in many countries including India[2], Slovakia[3], Ghana[4] and Poland[5]. Scientists have focused on job accessibility[6], accessibility to supermarkets[7], and temporal

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[7] Widener M.J., Farber S., Neutens T., Horner M.: Spatiotemporal accessibility to supermarkets using public transit: an interaction potential approach in Cincinnati, Ohio. Journal of Transport Geography, 2015,Vol. 42, pp. 72–83.

variability of accessibility[8]. Challenges in public transport accessibility are of concern across societies and impact not only the disabled but also for people without physical disabilities. Especially in aging societies, architectural barriers are becoming an obvious and urgent problem.

In an aging society like Poland many infrastructure upgrades have been completed, but there is still a problem with public transport accessibility in many cities. For example, in Katowice, one of the highest populated cities in Poland, the public transport network reaches every district; however, there are places where residents are hindered by architectural barriers that make it difficult or even impossible to reach bus and tram stops. An example of such a district is the Tysiąclecia estate, located on the border between two cities: Katowice and Chorzów.

Tysiąclecie estate was created as a bedroom community to Katowice. The Tysiąclecia estate with an area of 2 km^2 consists of two parts: Tysiąclecie Górne estate and Tysiąclecia Dolne estate. A part of the estate (Tysiąclecie Górne) is located on the border with Chorzów which is an area with many public transport and urban planning problems that have not been addressed for many years. Currently, there are approximately 22,000 residents who live in who predominantly live in residential building of 4 to 25 floors.

The decision to build a housing estate for 20,000 people on the border of Katowice and Chorzów was made on July 7, 1959. Later the target number of residents increased to 30,000. Currently, many of the residents of this estate are parents with young children and elderly people with mobility problems. Public transport challenges have already been discussed by Komar[9], who extensively analyzed problems in the estates. In the current study only barriers that can limit access to bus and tram stop were identified and investigated.

A new application (https://arcg.is/1nnrjL) was created to collect geoinformation about architectural barriers. This database can be a critically important and useful tool for future city authorities and decision makers. The volunteered geographic information (VGI) can be harnessed to create, assemble, and disseminate geographic data provided voluntarily by individuals and will be used in future analyses.

To conduct this study it was necessary to consider different types of challenges including location of bus or tram stops and the speed and movement of different groups.

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Usually, elder people move slower and transitions take more time. Distance can also be a barrier for those who have mobility problems. The figures below show the speeds at which pedestrians can cover particular distances and the time needed to cover 1 km given a specific speed they are moving at (Fig. 5.1).

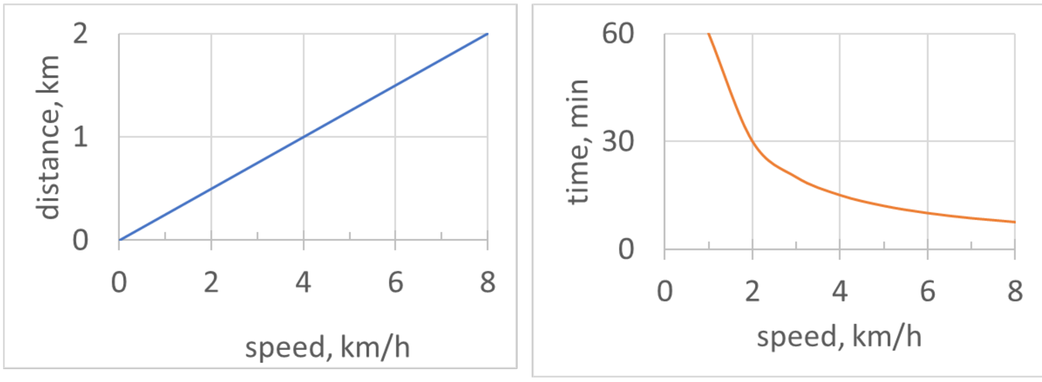

Fig. 5.1. Dependences of (a) the traveled distance (traveled over 10 mins) on speed (b) time, needed to travel 10 km, on speed
Rys. 5.1. Zależności (a) przebytej drogi (w ciągu 10 minut) od prędkości (b) potrzebnego czasu (do przebycia dystansu 10 km) od prędkości
Source: Own elaboration, 2022.

The speed of human movement is unique to each person and usually ranges from 4 km/h to 7 km/h. Speed depends on many factors (e.g., health condition, aspects, favorable or unfavorable weather conditions, road condition). It is assumed that the speed of brisk walking is approximately 6–7 km/h and normal walking is approx. 4–5 km/h. Elderly or sick people walking with a cane or walker, and those burdened with shopping bags or luggage, move more slowly. The distance a pedestrian must traverse also depends on whether a given architectural barrier is an obstacle and creates a less direct, more circular route.

5.2. Material and methods

5.2.1. Research area

This study's aim was to analyze the accessibility of public transport for residents of Tysiąclecia Górne (Katowice, Poland, Fig. 5.2) estate taking into account: (1) the location of stops; (2) different modes of transportation: bus (B) and trams and two different directions of travel: a way from Tysiąclecie Górne estate to Katowice city center (TK), and a way back from Katowice city center to the Tysiąclecie Górne estate (KT), due to a fact that localization of the bus stops in these two cases is different. (T); (3) infrastructure elements in the vicinity of stops that limit or even prevent access to stops; and (4) timetables and the number of bus and tram lines. The problems of public transport accessibility for residents of Tysiąclecia estate concern not only people for whom architectural barriers (stairs, high curbs, no ramps) constitute a problem in moving (PPM) (i.e., people on crutches, people using a walker with reduced mobility, or parents with small children) but also people for whom architectural barriers are not a problem (PNP).

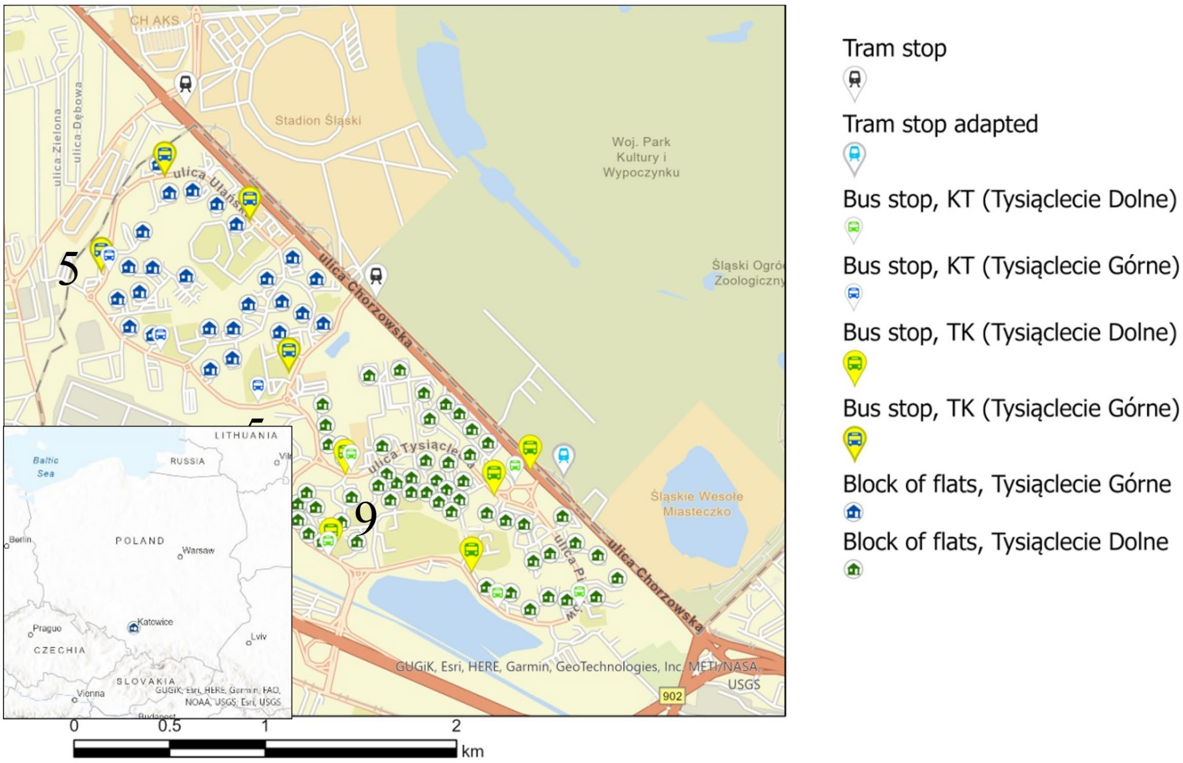

Fig. 5.2. Location of the blocks of flats in Tysiąclecie estate, with division to Tysiąclecie Górne and Tysiąclecie Dolne, bus and tram stops (only one tram stop (blue) has been adapted for people with special needs). Two different direction of travel has been analysed (1) from Tysiąclecie Górne estate to Katowice city center (TK), and (2) from Katowice city center to the Tysiąclecie Górne estate (KT). The numbers indicates the number of bus and tram lines that reach selected stops.

Rys. 5.2. Lokalizacja bloków na osiedlu Tysiąclecie Górne i Tysiąclecie Dolne, przystanków autobusowych i tramwajowych (kolorem niebieskim oznaczono jedyny przystanek tramwajowy przystosowany dla osób o szczególnych potrzebach). Na rysunku wyszczególniono dwa kierunki podróży (1) z Tysiąclecia Górnego do centrum Katowic (TK) oraz (2) z centrum Katowic do os. Tysiąclecia Górne (KT). Liczby wskazują na ilość linii autobusowych i linii tramwajowych dojeżdżających do wybranych przystanków

Source: Own elaboration, 2022.

5.2.2. Methods

The analysis was preceded by a study of the location of stops and the number of bus and tram lines all residents have access to (with and without architectural barriers) within the estate, as well as a survey of residents of Tysiąclecia Górne estate. In summary, in Tysiaclecia estate there are a lot of bus stops in both directions (TK, KT) and only three tram stops. Tram stops in both directions (TK, KT) are located on opposite sides of each other, whereas bus stops to and from city center are not located in close vicinity.

To conduct this study the following methods were used (1) survey – to learn the opinions of estate residents about the accessibility of public transport; and (2) geographical information systems (GIS). GIS tools and technique were used to perform time-distance and buffer analyses of public transport network connections and accessibility. GIS also was used to analyze the profiles of trackway based on data acquired from airborne laser scanning (ALS). Time-distance analyses were performed using ArcGIS. The ALS data was analyzed using the geoportal.gov database and point cloud viewer (geoportal.gov.pl).

5.2.2.1. Interview

The survey was used as a data collection tool to obtain opinions about public transport from residents. The survey included a mix of closed and open-ended questions. On February 1–14, 2022, 30 citizens of Tysiąclecia Górne estate were asked within interview face to face meeting the following questions:

1. Do you think there are any problems with access to public transport in Tysiąclecia estate?
   YES / NO
2. If the answer was "YES" to question 1, then:
   a) Do the problems relate to the location of the stops: YES / NO
      What do you think is the most important problem?
   b) Do the problems relate to infrastructure: YES / NO
      What do you think is the most important problem?
   c) Do the problems concern the timetables: YES / NO
      What do you think is the most important problem?

GIS: Time-distance analyses (buffer and network connection)

Generating Service Areas tools were used to analyze transportation problems related to accessibility and the determination of service areas. Analyses of distance and walking-time were performed using different tools (such as buffer and walking-time area and closest facility) in ArcGIS software. With ArcGIS it is possible to conduct research that considers not only distance but also topography and other features of the research area, as well as the speed and direction of pedestrian movement.

ArcGIS tools linked to Network Analysis such as "Buffer" and "Walking-time area" were used to find the area that covers a given distance from a selected point (bus/tram stop), to answer the following questions: where can people go within a set period of time and what areas are within a given distance of selected bus or tram stops? The areas were calculated based on travel mode (walking) and measure (time or distance). The point features around which areas were calculated included: bus stops toward Katowice city center, bus stops away Katowice city center, tram stops toward Katowice city center, tram stops away from Katowice city center.

Using the Overlay Layers tool to overlay the buffer with the layer containing stops, the following question was investigated "Which buildings are within selected distance of the bus stop or tram stop?" The answer was obtained by creating a selected distance buffer around the stops. The result was a layer of those buildings within selected distance of the stop, or a walking-time area that can be covered within a specified time or walking distance. "Closest facility" tool was used to find the nearest features and rank the distance to them. Results from this tool were used to answer the following questions: What are the road distances between places, what is the nearest bus stop from a selected building, and which buildings can be reached in the shortest walking time from a selected bus/tram stop? How long would the trip be?

To find what's nearest, the tool can measure using either a straight-line distance method or a selected travel mode. In this analysis a straight-line distance method couldn't be used to analyze public transport accessibility due to the fact that straight lines between two points can be significantly shorter than the real distance of network lines. Measurements must be made along walkways.

In this analysis available travel modes (attribute and parameters) were determined as follows: preferred for pedestrian, avoid roads unsuitable for pedestrians, and avoid private roads. Find Nearest returned a layer containing the nearest features and a line layer that linked starting locations to their nearest locations. These tools were used to determine the area that covers a given distance or time that could be traveled by a pedestrian from bus or tram stops.

GIS: Analysis of the ALS data to understand profile of the trackway

Airborne Laser Scanning (ALS) also known as Light Detection And Ranging (LiDAR)[10] (Wehr and Lohr, 1999) was used as a rapid, highly accurate, and efficient method of capturing 3D data for the trackway next to the tram stop. Airborne laser scanning was used to collect high-resolution data for generation of a digital surface. The ALS data originated from LIDAR PL-EVRF2007-NH symbol: 6.130.29.14.1 (actualization: 2020/05/08). The analysis was done in geoportal.gov.pl.

5.3. Results

There have been many studies of public transportation accessibility in different part of the world[11]; however, scientists usually focus on accessibility to supermarkets[12], selected public services and jobs[13], and temporal variability of accessibility[14]. Some studies have focused on public transport accessibility for wheelchair users and disabled people[15]. Despite increasing public investment in transport, and implementing large projects that give residents more opportunities for efficient movement, there are still many locations where access to public transport is difficult[16]. This study focused on one of these locations – Katowice, Silesian Agglomeration.

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[14] Stępniak M., Goliszek S.: Spatio-Temporal Variation of Accessibility by Public Transport – The Equity Perspective. [In:] Ivan I., Singleton A., Horák J., Inspektor T. (ed.): The Rise of Big Spatial Data. Lecture Notes in Geoinformation and Cartography. Springer, Cham 2017, pp. 241–261.

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5.3.1. Interview

When surveyed, residents for whom architectural barriers do not pose any problems (PNP) most frequently reported the following difficulties with public transport accessibility:

1. inadequate public transport timetables in the evening, night, and weekend hours including too few connections between the Tysiąclecie Górne estate and Tysiąclecia Dolne estate, and a small number of bus connections from the centre of the neighbouring city of Chorzów.
2. location of stops – the distance from stops is a problem for people returning with shopping bags or wanting to get to the train station or airport with heavier luggage; also the long distance to stops affects the sense of safety of residents returning from work at night and is burdensome in unfavourable weather conditions.

The second group of respondents were people with mobility problems (PMP) due to architectural barriers. This group included people on crutches, people with mobility impairments using a walker, or parents of young children. When surveyed, residents for whom architectural barriers such as stairs, high curbs, or no existing ramps were a problem in moving (PPM), the most frequently reported problems with public transport accessibility were:

1. architectural barriers – physical barriers to, or no access at all, to tram stops in the Tysiąclecie Górne estate, numerous stairs, no ramp, no handrails on both sides of the stairs, paved sidewalks with passenger vehicles, and high curbs
2. location of stops – the distance from stops is a problem for people returning with shopping, wanting to get to the train station or airport, or traveling with a child in a pram; the long distance from stops affects residents' sense of safety when returning at night, and the long distances are troublesome in unfavourable weather conditions
3. unadjusted public transport timetables in the evening, night, and weekend hours

Survey responses suggest the city does not respond to the public transport needs of its citizens. The estate is located within Katowice but stops located on the border of the zones seem to belong to "nobody". For example, tram stops located exactly on the border of cities are not adapted to the needs of the disabled, the elderly, or people with mobility problems and may even be completely inaccessible. Existing tunnels with steep stairs, high curbs, and no gentle declines or lowering ramps adapted to people on crutches, wheelchairs, children's prams, or walkers are an insurmountable obstacle to accessing the stop. A simple solution to this lack of access – creating a crossing at a nearby crossroad – would facilitate access to public transport for everyone but has never been tried.

5.3.2. Accessibility of the tram stop – case study 1

The tram stops at Tysiąclecie Górne estate are accessible only for those people who have no mobility problem. Both tram stops (Chorzów Stadion Śląski – Chorzów Silesia Stadium and Park Śląski Wejście Głowne – Chorzów, Silesia Park, Main entrance) near Tysiąclecie Górne estate have been inaccessible for Group PPM. The detailed analysis of the area nearby Chorzów Stadion Śląski – Chorzów Silesia Stadium, showed that the tram stops located exactly on the border of cities are not adapted to the needs of the disabled, the elderly, people on crutches, people using a walker, nor parents with their babies. Existing tunnels have steep stairs, high curbs, and a lack of gentle declines and ramps adapted for people on crutches, wheelchairs, people with walkers, and children's prams.

Fig. 5.3. Comparison of the distance to go as a linear and along network that must be passed by people (PNP and PPM) and existing architectural barriers

Rys. 5.3. Porównanie odległości, którą muszą pokonać piesi (PNP i PPM) w linii prostej oraz wzdłuż ulic uwzględniając istniejące bariery architektoniczne, by dotrzeć z wybranego bloku do przystanku tramwajowego

Source: Own elaboration, 2022.

Moreover, usually, people, with mobility problem (PPM) must travel at least twice as long compared to others (PNP) due to the steep stairs leading to tram stops ("Chorzów Silesia Stadium" and "Chorzów Silesian Park, main entrance"). The drawings show the differences between the distance in a straight line from one of the buildings and the actual distance pedestrians PNP and PPM must travel. The actual distance is greater than the straight line. In the case of people PPM, with architectural barriers this distance may be even doubled (Fig. 5.3).

Concerning the "Chorzów Silesian Stadium" tram stop, people can get to the tram in the direction of Chorzów; however, people traveling from the estate to the Chorzów Stadion Śląski tram stop and to Katowice by tram have to overcome high curbs next to the trackway. Moreover, the trackway has stone track without a pedestrian crossing.

Based on the analysis of the height profile within the trackway using LAS data (Fig. 5.4) it is evident there is no lowering capability; the difference in height is at least 20 cm which makes the transition inaccessible for the most PPM people. At the “Chorzów Silesian Park, main entrance” it was observed that the tram stop was suitable and favorable for PPM people as there was a pedestrian crossing from one site to another site of trackway.

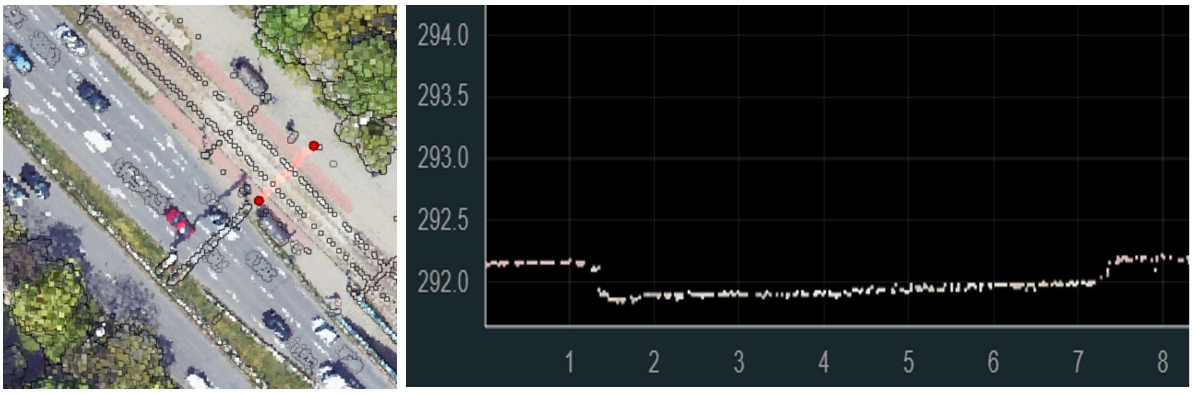

Fig. 5.4. Height profile of the trackway (based on ALS data, created at geoportal.gov.pl), y-axis presents the height of the trackway in centimeters, while x-axis presents the distance in meters. This stop is not adapted to people with special needs
Rys. 5.4. Profil wysokości torowiska (na podstawie danych ALS, utworzonych na geoportal.gov.pl), oś y przedstawia wysokość torowiska w centymetrach, a oś x odległość w metrach. Przystanek ten nie jest przystosowany dla osób o specjalnych potrzebach
Source: Own elaboration.

Another problem for PPM was evident from the survey: when PPM people tried to get into the tram at Chorzów, Silesian Stadium the distance between the sidewalk and the stairs to board the tram is too far (a distance of about several tens of centimeters (Fig. 5.5). It has happened that the wheels of the trolleys get stuck between the car and the stop.

Fig. 5.5. Example of the architecture barrier: a long distance between tram and sidewalk makes this stop not adapted to people with special needs
Rys. 5.5. Przykład bariery architektonicznej: duża odległość między tramwajem a chodnikiem sprawia, że przystanek ten nie jest przystosowany dla osób o specjalnych potrzebach
Source: Own elaboration.

5.3.3. Determination of the service areas: temporal and spatial analysis – case study 2

The Generating Service Areas tools were used to determine the service areas that cover a given distance from the bus or tram stops to the residences. The analysis took into account:

- two different modes of transportation: buses (B) and tram (T),
- two different directions of travel (1) a way from Tysiąclecie Górne estate to Katowice city center (TK), and (2) a way back from Katowice city center to the Tysiąclecie Górne estate (KT), due to the fact that the location of bus stops in these two cases is different.

The cutoff range in this analysis was between 0 km to 0.1 km, 0.1 km to 0.25 km, and 0.25 km to 0.5 km. It was observed, in case of travel mode (B,TK), that the distance to the bus stop from the block of flats was less than 0.5 km, but for PMP the actual distance from house to bus stop can be up to 1 km with architectural barriers. If the speed of this person is 5 km/h, this person must go on foot for nearly 10 minutes to get to the nearest stop (Fig. 5.6).

In the case of B,KT travel mode (Fig. 5.7) it was observed that for many people the distance from the bus stop in the city center to their house can be significantly longer than the B,TK travel mode of going from the city center to their houses. Moreover, the areas of the cutoff range of 0.5 km from bus stops to the houses doesn't cover whole areas of the estate. That can be a problem for people, especially for people with special needs (PMP). An actual distance from house to bus stop can be up to 1 km, and the time needed to get there can be up to 10 minutes (if speed of the motion is 5 km/h).

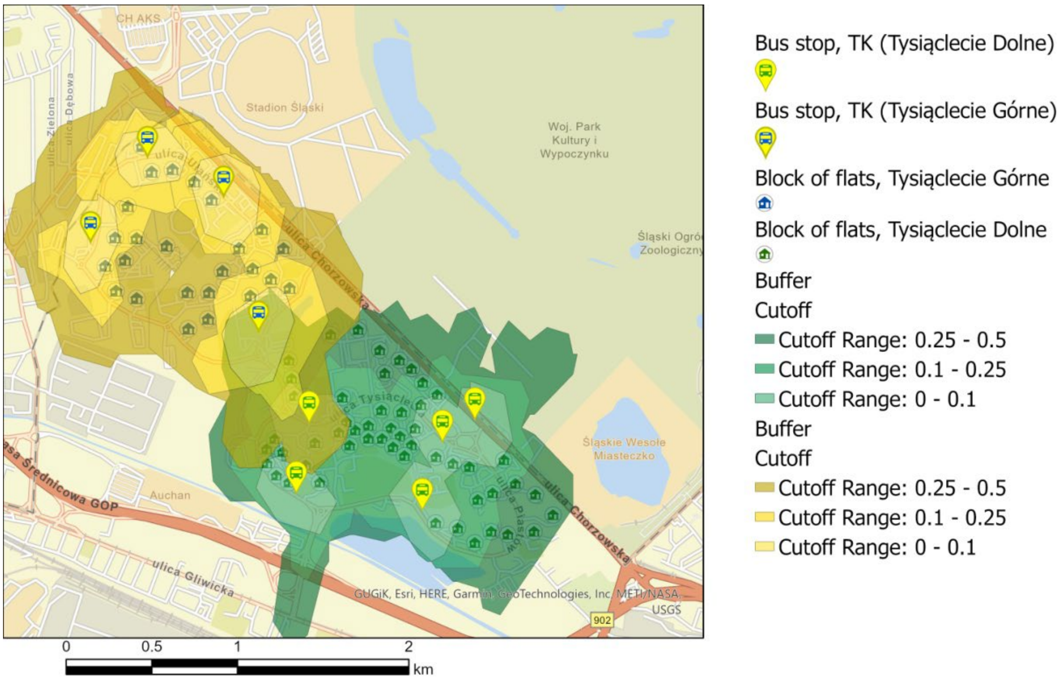

Fig. 5.6. Analysis of public transport accessibility (B, TK). The distances ranged from 0 km to 0.1 km, 0.1 km to 0.25 km, and 0.25 km to 0.5 km

Rys. 5.6. Analiza dostępności do środków transportu publicznego – przystanków autobusowych (B, TK). Odległości: od 0 km do 0,1 km, 0,1 km do 0,25 km i 0,25 km do 0,5 km

Source: Own elaboration.

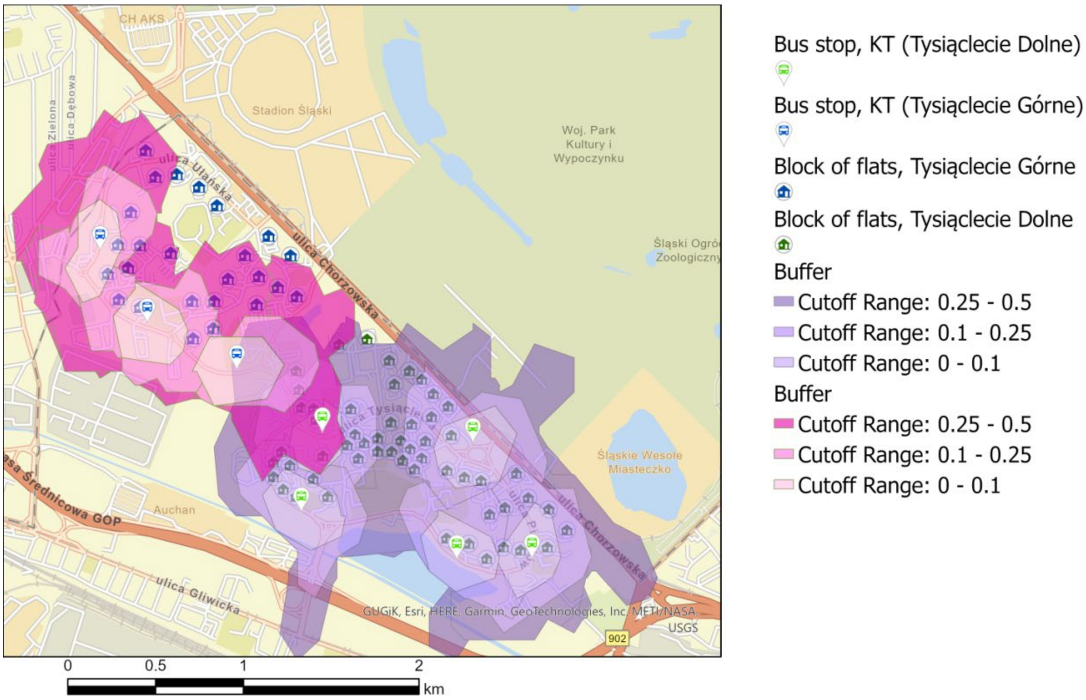

Fig. 5.7. Analysis of public transport accessibility (B, KT). The cutoff ranged from 0 km to 0.1 km, 0.1 km to 0.25 km, and 0.25 km to 0.5 km

Rys. 5.7. Analiza dostępności do środków transportu publicznego – przystanków autobusowych (B, KT). Odległości: od 0 km do 0,1 km, 0,1 km do 0,25 km i 0,25 km do 0,5 km

Source: Own elaboration.

The analysis of tram stop accessibility (T, TK and KT) showed two tram stops were not adapted to PMP. A distance to the nearest tram stop accessible for PMP can be a few kilometers (Fig. 2.8), whereas for PPN a distance can be as short as 0.5 km, but only for residents from a small number of blocks of flats; for the rest of the residents these distances were much farther.

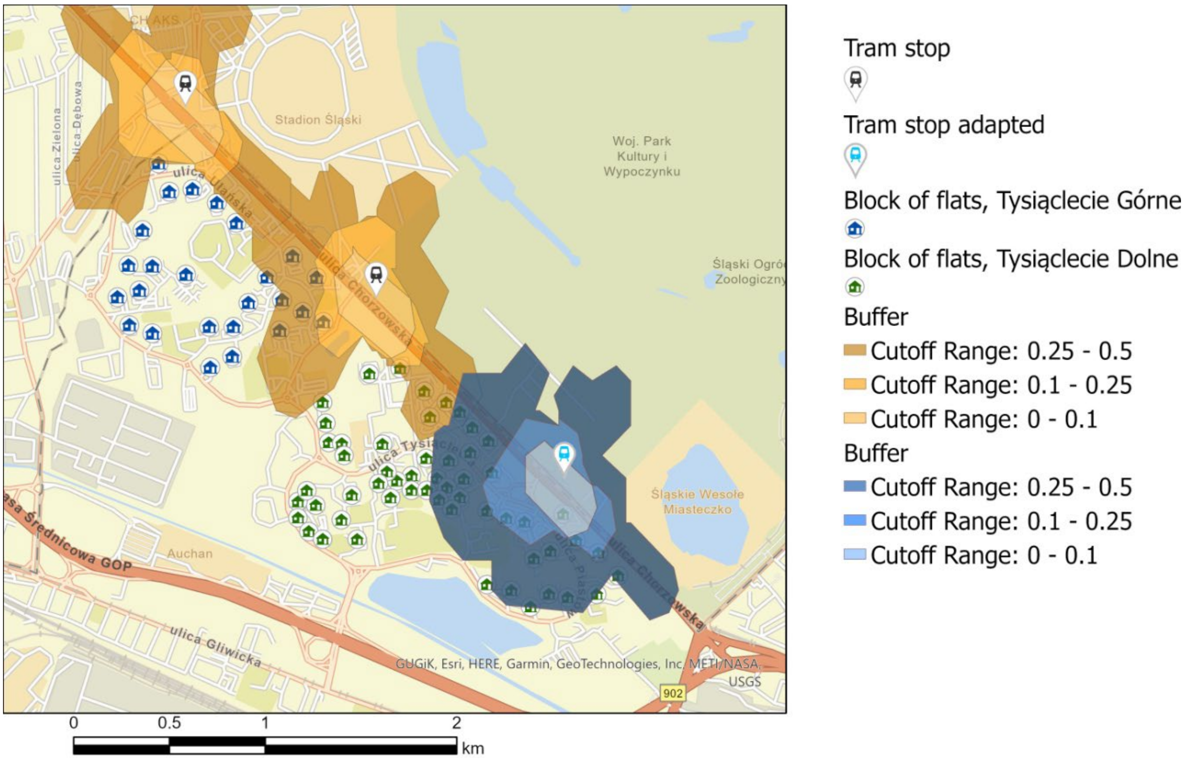

Fig. 5.8. Analysis of public transport accessibility (T, TK and KT). The cutoff ranged from 0km to 0.1 km, 0.1 km to 0.25 km, and 0.25 km to 0.5 km

Rys. 5.8. Analiza dostępności do środków transportu publicznego – przystanków tramwajowych (T,TK i KT). Odległości: od 0 km do 0,1 km, 0,1 km do 0,25 km i 0,25 km do 0,5 km

Source: Own elaboration.

Because tram stops adapted for people with special needs are far from Tysiąclecie Górne estate, upon further analysis the author decided to focus only on travel modes accessible to everyone. Temporal analysis enabled the author to observe how much time someone needs to get from the residence to the nearest bus station. Most of the citizens who move with a speed at least of 5 km/h need about five minutes to get to the nearest bus stop towards the city centre, whereas people who travel from the city centre to their residences need much more time to travel the distance between the nearest bus stop to their homes. Less than 50% of the block of flats were situated where walking time was up to five minutes (Fig. 5.9).

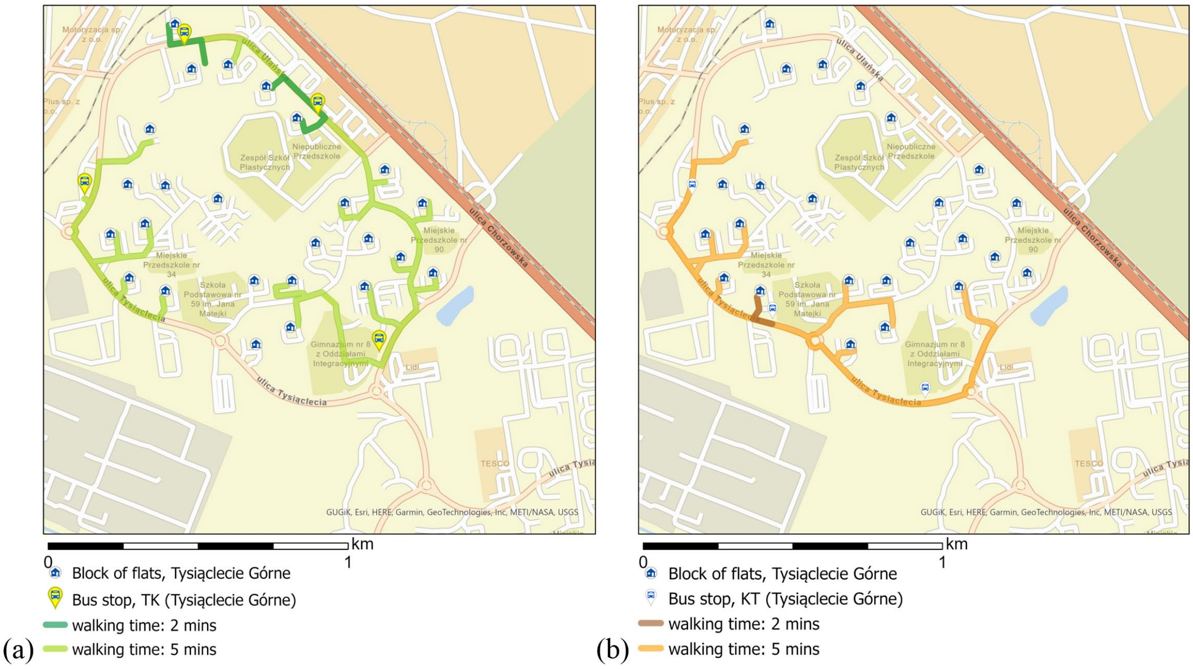

Fig. 5.9. The analysis of the time and distance needed to get to the bus stop towards the center of Katowice (a) and from the city center (b), if a speed of the pedestrian is 5 km/h

Rys. 5.9. Analiza czasowa i przestrzenna: czas potrzebny na dotarcie do przystanku autobusowego i odległość pomiędzy blokami a przystankami autobusowymi, dla linii komunikacji miejskiej (a) w kierunku centrum Katowic oraz (b) z centrum Katowic (b), przy założeniu, że pieszy porusza się z prędkością 5 km/h

Source: Own elaboration.

5.3.4. Connection between Tysiąclecie Dolne and Tysiąclecie Górne estate in the evening and during weekends – case study 3

In studying the location of stops it was clear that bus routes were different for buses from the city center and to the city center of Katowice. Two tram stops closest to the Tysiaclecie Górne estate were not adapted to the needs of the disabled, the elderly and the sick, those who use crutches, people with mobility issues, or parents with young children for whom architectural barriers are a huge obstacle. One can get to the Tysiaclecie Dolne estate from the city center using nineteen bus lines, while Tysiąclecie Górne estate was serviced by only five lines.

Analyzing the bus timetables between Tysiąclecie Dolne estate and Tysiąclecie Górne estate, it was clear that on weekends, and during the night and evening hours on working days, a passenger often must wait almost half an hour to cover a distance of about 2 km by public transport connecting both parts of the estate. It often happens that buses go like a "herd" within a few minutes, followed by a break of about half an hour in communication. The time needed to get on foot from Tysiąclecie Dolne estate to

Tysiaclecie Górne estate (the blocks located near the border with Chorzów, northwest) depend on the speed of motion. If someone moves with a speed of 6 km/h walking time can be about 15–20 minutes. If someone moves slower, the time increases to 25 minutes or more (Fig. 5.10).

Further, more detailed distance-time analysis presented the distance that could be reached by people if they moved with a different speed. This concerned situations where someone is travelling (B, KT and B, TK) in the evening or during the weekend and decides to walk on foot from Tysiąclecie Dolne to Tysiąclecie Górne. In this case, the following variables were taken into account: (1) human movement speed between 3 km/h and 6 km/h (2) location of the bus stops and houses (3) architectural barriers and network connections accessible for PPM people (4) slope and topography, and (5) time of the motion: between 10 and 20 mins.

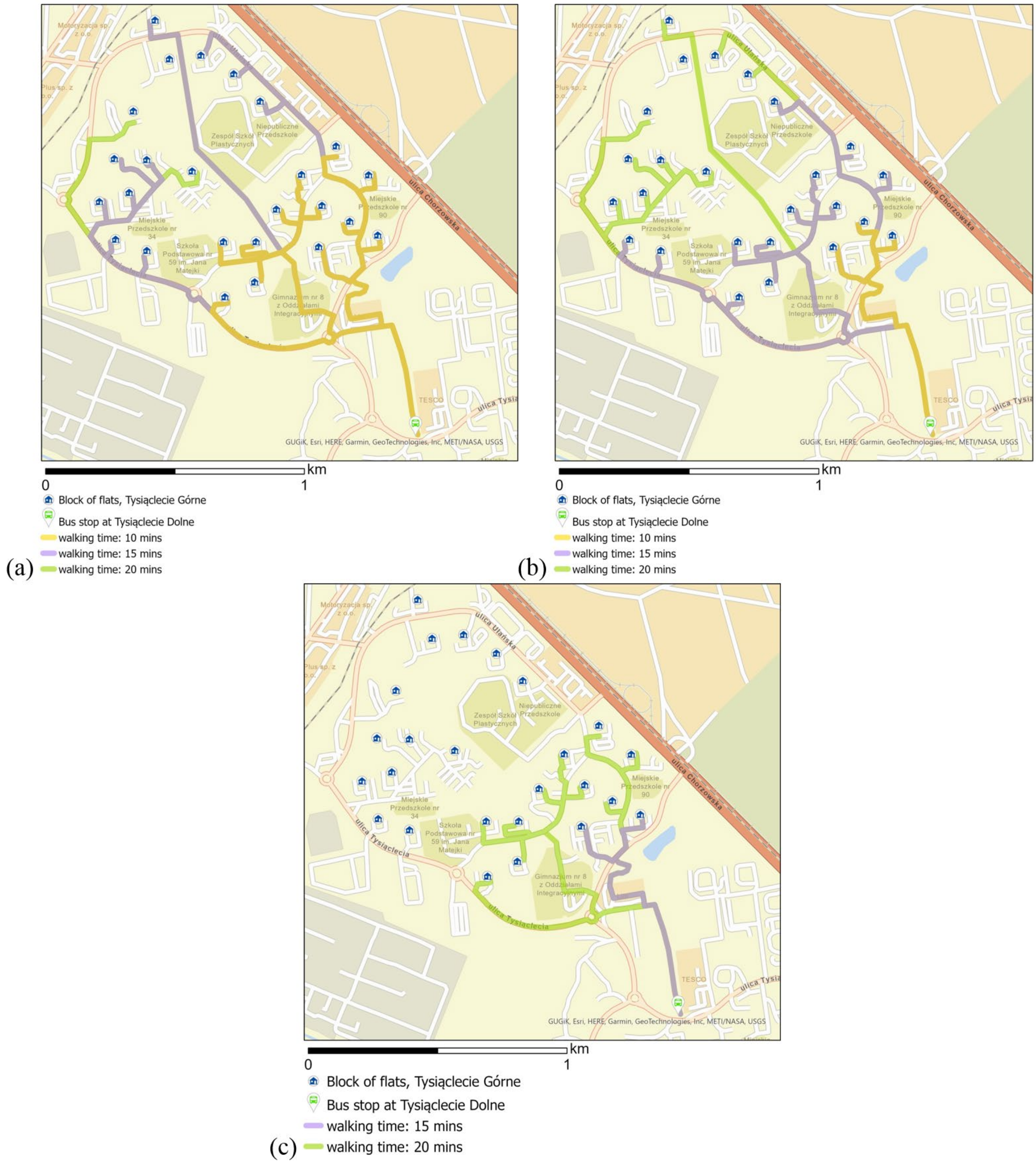

Fig. 5.10. The distance that can be reached by pedestrian depends on the speed (a) 6 k/m; (b) 5 km/h, and (c) 3 km/h, respectively), if they move from Tysiąclecie Dolne to Tysiąclecie Górne estate on foot, due to a lack of connection between two parts of the estate

Rys. 5.10. Odległość, jaką może pokonać pieszy, w zależności od prędkości z jaką się porusza (a) 6 k/m; (b) odpowiednio 6 km/h i (c) 3 km/h), w ciągu 10, 15 i 20 minut, podróżując z ostatniego przystanku zlokalizowanego na Os.Tysiąclecie Dolne w kierunku Os. Tysiąclecia Górnego, w przypadku braku połączenia między obydwiema częściami osiedla

Source: Own elaboration

5.4. Conclusions

This study of public transport accessibility based on a survey and GIS analysis identified the most significant problems in Tysiąclecie Górne estate. Residents indicated the most significant problems were inadequate public transport timetables and the location of stops. The distance from or to stops is a problem not only for people returning from shopping or wanting to get to the train station or airport with heavier luggage, but also for people with mobility problems. Only some stops are adapted to people with special needs.

Architectural barriers make it impossible or difficult to get to certain stops (e.g., numerous stairs, no ramp, no handrails on both sides of the stairs, paved sidewalks with passenger vehicles, high curbs). The long distances from stops affect residents' sense of safety when returning at night. These problems are known but have not been addressed. Adaptation of routes to address the needs of residents should be undertaken as soon as it is possible. The different methods for the analysis of public transport accessibility were presented in this part of monography. To help city authorities and decision makers a new application (https://arcg.is/1nnrjL) has been also created by the author of this monography to collect geoinformation about architectural barriers. This database might be used as a critical tool for decision makers who wish to make public transport more accessible. The volunteered geographic information (VGI) can be harnessed and used as a tool to create, assemble, and disseminate geographic data provided voluntarily. The assembled data will be analysed in the future.

DOI:10.34918/87426

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6. THE POSSIBILITY OF USING INDUCTION LOOPS AS A SOURCE OF INFORMATION ON VEHICLES

6.1. Introduction

Vehicle Weigh-In-Motion stations provide detailed data on each passing vehicle. The data includes information on vehicle length, number of axles, axle spacing, total weight, individual wheel and axle loads and vehicle class according to the standard adopted by the road authority. As part of the research and development project co-financed by the European Regional Development Fund through the Silesian Centre for Enterprise, APM PRO sp. z o.o. developed the iWIM weighing computer, which processes and analyses data from individual sensors installed, among others, in the road surface. The computer contains a module that enables reading the magnetic profile of a vehicle passing through a station. This module is designed to be a separate unit.

WIM stations are set up to exclude from traffic vehicles that exceed the permitted standards[3]. There are different limitations for various vehicles. There are many configurations of Weigh-In-Motion stations and now they usually do not have a connection to government vehicle databases. Therefore, there is a need to classify the type of vehicle based on data collected by a WIM station.

The loop recorder allows the creation of a classifier based on the signal from a single induction loop, which has the advantage, among other things, of not processing personal data, unlike systems using automatic number plate recognition (ANPR) cameras.

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[3] Raport NIK, Ruch pojazdów przeciążonych na obszarach zurbanizowanych https://www.nik.gov.pl/plik/id,23352,vp,26070.pdf, [accessed in May 2022].

Magnetic signature analysis makes it possible to extract vehicle characteristics such as number of axles and vehicle length, which consequently allows them to be classified.

Two standards are typically used to classify vehicles: COST 323[4] and TLS 8+1[5]. Research into the use of induction loops as sources of vehicle information shows that it is possible to recognise vehicle length[6], number of axles[7] and vehicle class[8] from loop data. Algorithms proposed by various authors enable the extraction of specific vehicle features. In this study, it was decided to investigate the suitability of machine learning algorithms for vehicle feature extraction and classification based on a single induction loop.

6.2. General description of the wim station structure

The Weigh-In-Motion (WIM) station is used for dynamic weighing of vehicles at high speeds while maintaining smooth traffic flow. Weighing at high speeds is possible by suitable sensors embedded in the road surface. The most common types of sensors for measuring weight are strain gauges and piezoelectric quartz sensors. The construction of the measuring station involves installing individual sensors in the road surface. The following are incorporated on the approach side (respectively): induction loops, load cells (strain gauges or quartz piezoelectric), piezoelectric sensors and, optionally, another two sets of load cells. ANPR cameras, 3D scanners, a weather station and CCTV cameras are located on the gantry structure, which is just behind the last load cells. Induction loops are responsible for detecting the approach and activating the measuring track of the weighing station and the 3D scanner. When a vehicle approaches the induction loop, images from ANPR and CCTV cameras are also taken.

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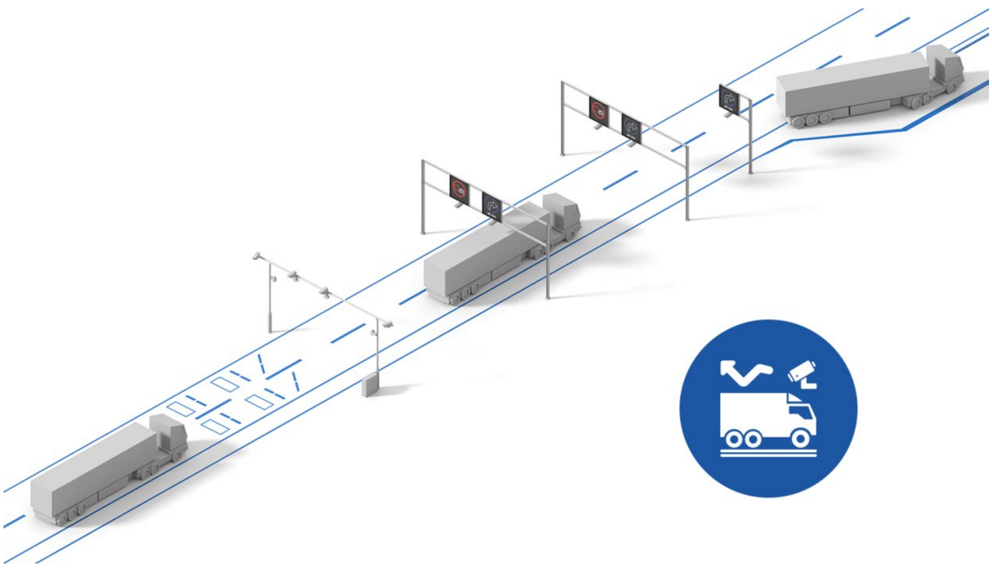
[4] Jacob B., O'Brien E., Jehaes S.: COST 323 Weigh-in-Motion of Road Vehicles, 1999. http://www.is-wim.org/doc/wim_eu_specs_cost323.pdf, [accessed in May 2022].

[5] TLS2012, Technische Lieferbedingungen für Streckenstationen. BAST, 2012. https://www.bast.de/BASt_2017/DE/Publikationen/Regelwerke/Verkehrstechnik/Unterseiten/V5-tls-2012.pdf?__blob=publicationFile&v=1, [accessed in May 2022].

[6] Gajda J., Sroka R.: Vehicle classification by parametric identification of the measured signals, XVI IMEKO World Congress, Vienna, Austria, 2000.

[7] Marszalek Z., Zeglen T., Sroka R., Gajda J.: Inductive loop axle detector based on resistance and reactance vehicle magnetic profiles, Sensors, 2018.

[8] Burnos P., Gajda J., Piwowar P., Sroka R., Stencel M., Zeglen T.: Measurements of road traffic parameters using inductive loops and piezoelectric sensors, Metrology and Measurement Systems, 2007, Vol. 14, No. 2, pp. 187–203.



Rys. 6.1. Stacja ważenia pojazdów w ruchu – schemat ogólny
Fig. 6.1. Vehicles Weigh in Motion station – general scheme
Source: Company materials.

6.3. Method used

6.3.1. Features selection and extraction

The proprietary iWIM system was installed for the first time at a test station located on national road 44 in the Silesian Voivodship, Mikołów County. 1799 records for the learning set were retrieved from the test station, and then additional 118 records as the test set. The datasets were selected in such a manner that the number of records from each class was similar.

The first step in preparing the learning set was to analyse the signals received to determine their statistical measures – including mean, weighted mean and median. Also, the individual peaks from the signal distributions using the Fast Fourier Transform and the chirp Z-transform were included in the feature vector.

There were 64 features in the vector created to develop a classifier to recognise vehicle category. A vector of 141 features was used to create a regressor that identifies vehicle length, while a vector of 167 features was used to identify the number of vehicle axles.

6.3.2. Vehicle length recognition

For the regressor recognising vehicle length, a method was chosen in which the data were standardised so that the mean value was 0 and the standard deviation was 1. In this case, the standardisation procedure achieved better results than with unstandardised data. Next, a factor analysis was performed using the Factor Analysis algorithm to find the vector features that had the greatest impact on the correct prediction of vehicle length. The use of this algorithm also made it possible to reduce computational complexity. The final stage was to test several classification algorithms in terms of the accuracy of the results obtained. The following algorithms were verified: random forest regressor, decision tree regressor, voting classifier (composed of random forest regressor and logistic regression), support vector machine and logistic regression. The random forest regressor showed the highest accuracy, averaging 85% for the 10 cross--validation results.

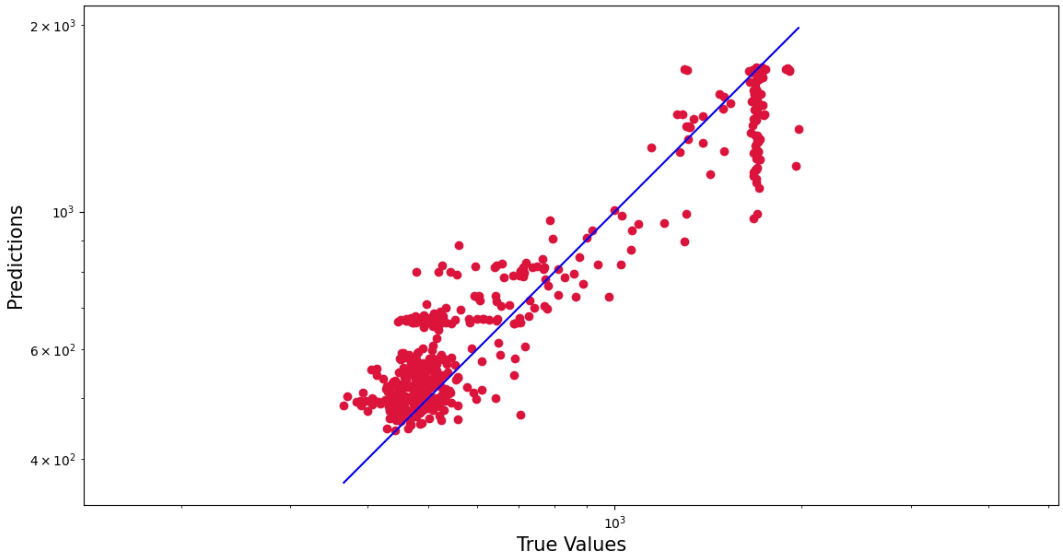


Fig. 6.2. Values estimated by regression to measured values of vehicle length
Rys. 6.2. Wartości estymowane przy pomocy regresora do wartości zmierzonych długości pojazdu

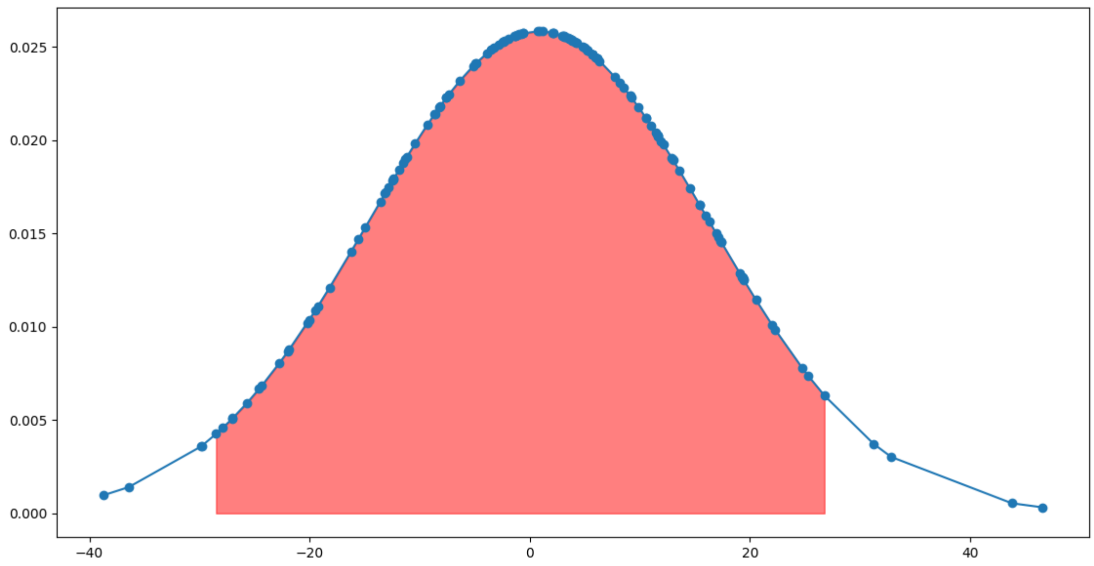


Fig. 6.3. Percentage distribution of deviations of the regressor-estimated value from the measured vehicle length value

Rys. 6.3. Procentowy rozkład odchyleń wartości estymowanej przy użyciu regresora od wartości zmierzonej długości pojazdu

A Shapiro-Wilk normality test was performed for the set of vehicle length results obtained. The value of the statistic was 0.99 and the p-value was 0.36 (for a random data set other than the teaching and test set). No grounds were shown for rejecting the hypothesis of normality of the data distribution. Using the properties of the normal distribution, it was found that 95.5% of the estimated values assume an accuracy of +/-26%. This estimation does not allow the obtained values to be taken as actual information about the passing vehicle but is sufficient to provide a general indication of whether the vehicle length was within one of four ranges: short (3–5 metres), medium length (7–9 metres), long (11–13 metres) or very long (15–19 metres).

Recognition of the number of axles on the vehicle

In the case of a classifier that determines the number of axles, the best results were obtained when standardising the vector of vehicle features. Then, after testing multiple classifiers, a random forest was selected as giving the best results. In this case, the use of factor analyses (after testing PCA, FA and ICA) was abandoned because they did not improve the detection of the number of axles. The random forest-based classifier gave the best results and showed over 99% accuracy on the test set in detecting the number of vehicle axles.

Table 6.1

Classification results for the number of vehicle axles

Actual number of axles	Classification accuracy	Number of samples in the test set	Number of misclassified	Number of samples in the learning set
2	100%	14	0	30
3	100%	14	0	30
4	100%	14	0	30
5	100%	14	0	30

6.3.4. Vehicle category recognition

The results of the classifiers discussed above could be used to create a very simple classifier dividing vehicles into four classes, as described in "Measurements of Road Traffic Parameters Using Inductive Loops and Piezoelectric Sensors"[9]. However, it was decided to explore the possibility of using the obtained data to develop a classifier that would classify vehicles according to the TLS 8+1 standard. The data vector was fed with results from the two classifiers described above. The dataset was then standardised for a standard deviation of 1 and a mean value of 0, this method in this case increased the effectiveness of the classification. No factor analysis algorithm was used (ICA, PCA and FA were tested) as this did not positively influence the classification results.

As before, several classifiers were tested: a support vector machine, logistic regression, decision tree, random forest, and a voting classifier composed of logistic regression and random forest.

The highest accuracy was obtained using the voting classifier, which gave an average of 98% efficiency for the ten cross-validation results. The results for each class are shown in the table.

[9] Burnos P., Gajda J., Piwowar P., Sroka R., Stencel M., Zeglen T.: Measurements of road traffic parameters using inductive loops and piezoelectric sensors, Metrology and Measurement Systems, 2007, Vol. 14, No. 2, pp. 187–203.

Table 6.2

Classification test results

Actual classes determined by the expert	Classification accuracy	Number of samples in the test set	Number of misclassified	Number of samples in the learning set
2	97%	70	2	251
3	96%	55	2	251
5	100%	61	0	251
7	99%	72	1	251
8	100%	78	0	251
9	97%	66	2	251
10	100%	15	0	42
11	99%	67	1	251

The small number of samples in the learning and test set for category 10 (motorbikes) is because, relative to the other vehicle categories, there is little motorbike traffic (there were only a few dozen journeys over several months of signal recording). Much of the data from motorbike journeys was not suitable for analysis because the induction loop does not cover the entire width of the lane, being in its centerline – many TLS Class 10 vehicles (motorbikes) passed outside the loop, preventing recording. The lowest classification accuracy was obtained for class 3 (trucks), 9 (truck tractors with semi--trailers) and 2 (cars with trailer) according to the TLS standard. As further work, it is planned to continue developing the classifier by applying fuzzy logic.

6.4. Results

Induction loops are embedded in the road surface. The vehicle approaching the loop triggers the whole measuring track of the weighing station. However, this is not the only function of induction loops. Passing through the loops allows the recording of vehicle's magnetic profile.

The placement of loops in the road, their layout and size are determined by the relevant standards among others TLS. The TLS standard allows for the construction of unified vehicle classification stations. It standardizes the classification of vehicles by class: 8 (trucks with trailer), 9 (truck tractors with semi--trailers), 7 (cars), 5 (buses), 3 (trucks), 2 (cars with trailer), 10 (motorbikes).

Data obtained from induction loops can be used to classify vehicles. There are devices available on the market that determine the vehicle category based on data obtained from two induction loops.

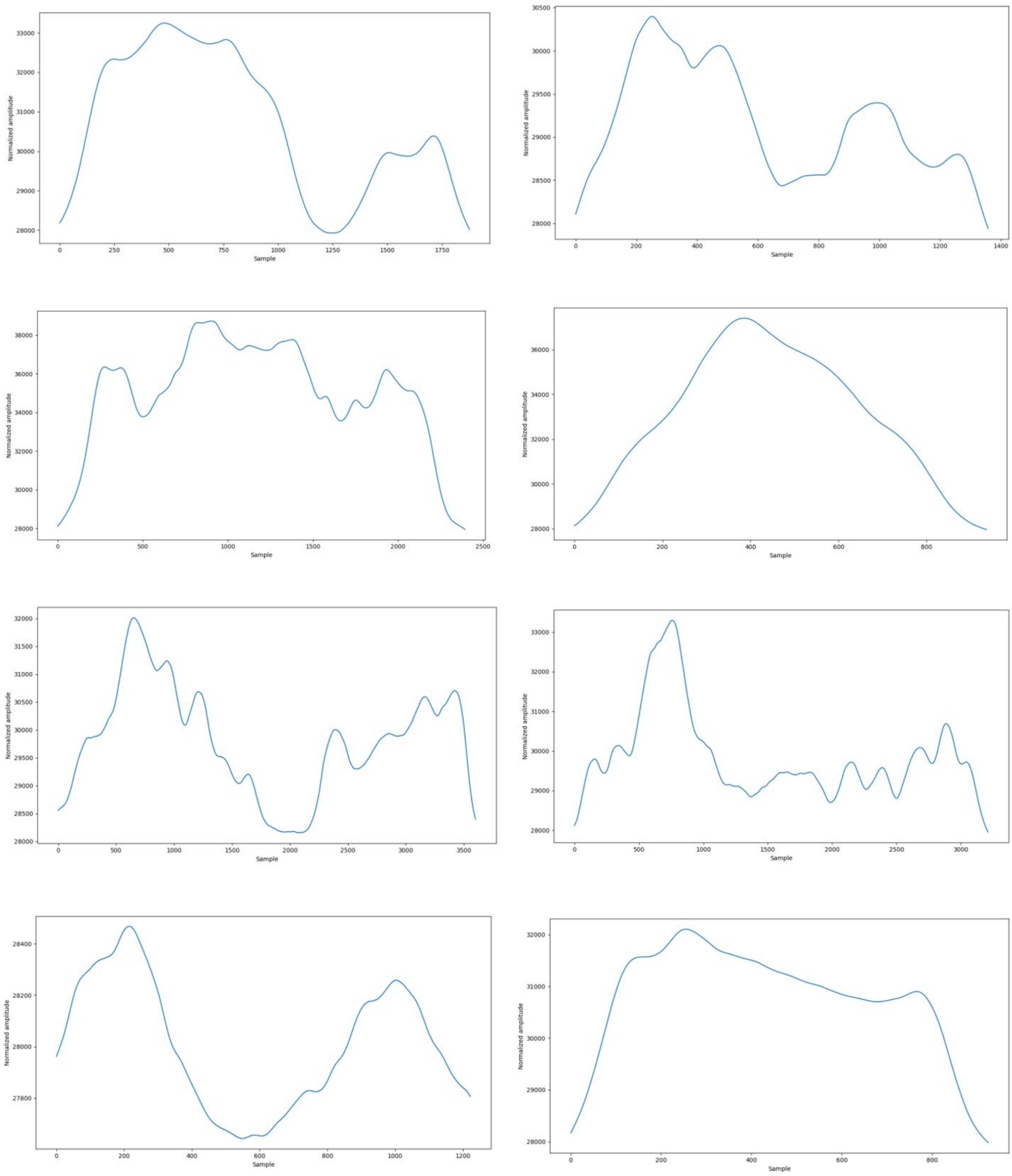


Fig. 6.4. Magnetic profiles of vehicles for classes (according to TLS 8 + 1): 2, 3, 5, 7, 8, 9, 10, 11
Rys. 6.4. Profile magnetyczne poszczególnych klas pojazdu (według TLS 8+1): 2, 3, 5, 7, 8, 9, 10, 11
Source: Own elaboration.

The research resulted in the development of a high-performance classifier. Using the Python programming language, a web service was created. The program processes the signal from the induction loop as an input parameter, then subjects it to a classification, this way obtaining vehicle class. The time from sending data to the web service to receiving a response with the vehicle class is approximately 500ms, which is sufficient for use in an industrial environment.

The designed classifier was deployed in a production environment when the iWIM weighing computer was first installed. This computer has a module for reading data from an induction loop at the aforementioned test station in Mikołów on National Road 44. Classification data is processed and stored in a database. Additionally, camera images are collected to verify the correctness of the classification by the classifier. The currently designed vehicle classification system obtains an accuracy of approximately 96%.

Based on the research, we conclude that it is possible to create a high accuracy classifier based on a single inductive loop. Such a solution in the future may replace more complex two-loop systems or those requiring additional sensors.

6.5. Discussion

Based on the magnetic profile, we can recognise: the number of axles of the vehicle, the vehicle length, and the vehicle classification. However, the described are computational methods that do not find deep connections as in the case of machine learning algorithms, hence the new approach proposed by the authors to the topic of recognition of individual vehicle features and classification, based on machine learning algorithms.

The literature proposes the application of classifiers that use two induction loops. However, it has been shown through research that data obtained from only one loop using the proposed method can give similar results. The use of a single loop for classification enables a significant reduction in the cost and installation time of the solution and may therefore allow widespread use of the solution on roads. The application of the developed vehicle classification method can also help in the creation of traffic structural maps, which improves road infrastructure management, road capacity and traffic safety.

The use of the induction loop as a source of vehicle information requires further research. In the course of the research, it was noted that the shape of the loop affects the signal and presumably also the information that is contained in the signal.

Acknowledgments

This research was co-financed by the Ministry of Education and Science of Poland under grant No DWD/4/21/2020 and thanks to APM PRO sp. z o.o. company, which under a research grant financed by the European Regional Development Fund via the Silesian Centre for Enterprise developed the iWIM weighing computer with a loop recorder as its component.

DOI:10.34918/87427

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7. COMPARISON OF ENERGY CONSUMPTION AND CO2 EMISSIONS IN THE LIFE CYCLE OF SELECTED ELECTRIC AND COMBUSTION VEHICLES

7.1. Identification of the problem

Electric cars can play a dual role in future. Firstly, they will traditionally be used to move goods and people, and secondly they could be used to store energy for balancing in renewable energy.

In both cases, it is important to know the full carbon footprint of electric vehicles relative to combustion vehicles. It is straightforward to compare the carbon footprint for the use phase of electric vehicles and combustion vehicles that run on a specific driving cycle. However, comparing the energy consumption and associated CO2 emissions during the production phase of vehicles and, in particular, during the manufacture of the materials from which the vehicles are built, is not straightforward. This article has been written with this in mind. It is an attempt to calculate the energy consumption and CO2 emissions over the life cycle of selected electric and combustion vehicles. Such calculations can be done with available data by students or renewable energy engineers. This is a good basis for a public discussion about the benefits of electric vehicles because publications available to non-engineers are often based on the feelings of the authors rather than on numerical data. The target audience for our article should therefore be students, engineers or readers interested in motoring who want to see how to estimate the energy consumption for the production of objects (in this case, a combustion car and an electric car) and how to calculate the CO2 emissions associated with it. We show in the article that it is not necessary to have dedicated computing programs or large

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computer processing power for this purpose. This simplified approach is quick and gives a good idea of energy levels and CO2 emissions. More complex models taking into account, for example, the exact place of production of each component from which the car is later built is possible, but was not considered here. Nor was the level of recycling of the material from which a given part is built considered separately for each part. Instead, it was considered on a general level, as an average share of recycling of a given material in the whole group in the automotive industry.

7.2. The lca method used

We have carried out life cycle analysis for many pairs of vehicles, but in this chapter we present only two types of one car model. One is a car with a combustion engine and the other is an electric vehicle. We chose Peugeot vehicles, model 208 because these vehicles are very popular in the EU, they occupy the top sales positions in the year 2021 in the EU market and most importantly they are twin vehicles. The aim of the calculations within the framework of the article is to compare how much energy is used to produce the component materials from which both vehicles are built, how much energy is used in the automotive industry to produce a combustion vehicle and its electric counterpart (also its batteries), how much energy is not used due to recycling, and later how much energy the analysed two types of cars consume during operation over a similar distance. At each stage, we additionally calculated the accompanying CO2 emissions.

Figure 7.1 shows the main stages of our analysis. For the analysis results to be reliably compared, it is necessary to select vehicles with similar performance. This means that the combustion engine (from the manufacturer's offer) must be powerful enough to achieve similar acceleration as the EV. In the case of the Peugeot 208, the acceleration time to 100km/h for the internal combustion vehicle with a 1.2 PureTech 96 kW engine and EAT8 gearbox is 8.7 seconds, while for the 100 kW electric version this time is 8.1 seconds. The combustion vehicle should also have an automatic transmission configured (for the 208 model this is the AISIN EAT8 transmission).

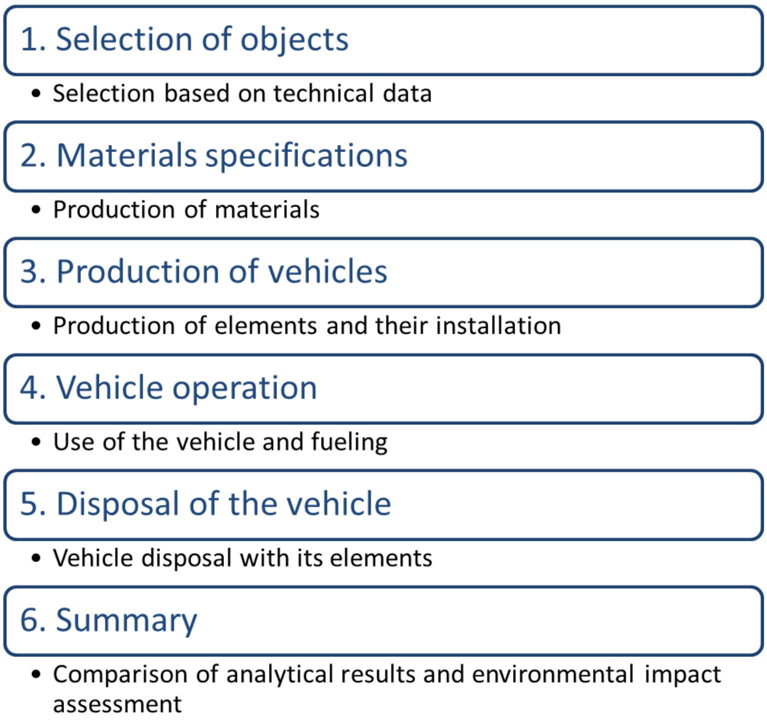

Fig. 7.1. Block diagram of the LCA analysis performed
Rys. 7.1. Schemat blokowy przeprowadzonej analizy LCA

The first step of the analysis is to determine which major groups of materials both cars are composed of. In our case, we assumed that we take into account the most important materials that both cars are composed of:

- Metals (steel, cast iron),
- Non-ferrous metals (copper, aluminium),
- Plastic group
- Rubber
- Glass
- Oil

Then, using literature data, we assumed the expected percentages of each material group in the mass of each car[3]. At this stage, a rather common mistake may be made if it is forgotten that an electric car should be analysed as two objects: separately the battery (the mass of the battery) and the rest of the vehicle (the mass of the rest of the vehicle after deducting the mass of the battery from its own mass)[4].

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[3] https://autokult.pl/4985,materialy-konstrukcyjne-w-nowoczesnych-pojazdach-samochodowych-cz-1; https://autokult.pl/4757,materialy-konstrukcyjne-w-nowoczesnych-pojazdach-samochodowych-cz-2.
[4] https://www.joanneum.at/life/aktuelles/news/news-detail/expert-notification-on-estimating-ghg-emissions-and-primary-energy-of-vehicles-tested-in-green-ncap-lca-methodology-and-data.

For our two analysed vehicles, we assumed that the contribution of the main material groups to their total mass (for the electric vehicle, the total mass is minus the mass of the entire battery bank) is as shown in Figure 7.2.

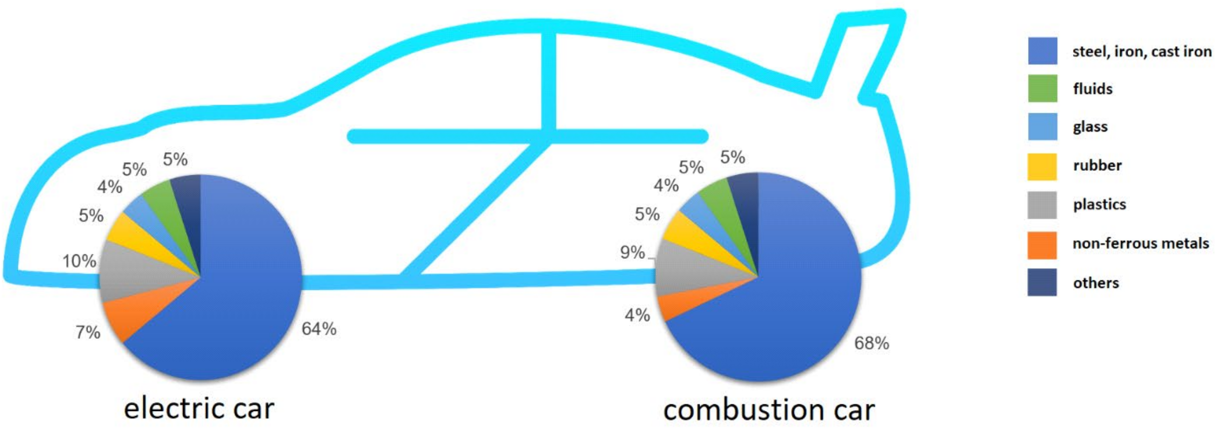

Fig. 7.2. Percentage of the main material groups in the total mass of the analysed vehicles
Rys. 7.2. Procentowy udział głównych grup materiałów w masie całkowitej analizowanych pojazdów

Then, based on data from the literature, we considered the amount of energy that is consumed in industry to produce materials from a given material group.

For example:

- arc furnaces to melt 1000 kg of steel consume on average 405–475 kWh[5],
- the production process of 1 kg of aluminium consumes from 53 kWh to 64 kWh of energy[6],
- the production process of 1 kg of copper consumes from 3889 kWh to 5556 kWh[7],
- the production process of 1 kg of elements from the plastic group consumes about 20–25 kWh/kg[8].
- the production process of one car tyre consumes between 259 kWh and 316 kWh[9].
- the production process for 1 kg of glass consumes 5–7 kWh[10].

For some material groups the exact calculation of their mass in a specific car is difficult (e.g. the proportion of steel by grade) but some materials are easy to estimate.

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[5] Zdonek B, Szypuła I.: Instytut Metalurgii Żelaza im. St. Staszica „Zmniejszanie emisji co2 w procesie elektrostalowniczym poprzez stosowanie alternatywnych materiałów nawęglających we wsadzie" – prace inż. 1, 2010.
[6] https://energyeducation.ca/encyclopedia/Aluminum.
[7] Leksykon naukowo-techniczny z suplementem. Warszawa: WNT, 1989. ISBN 83-204-0967-5.
[8] https://learn.openenergymonitor.org/sustainable-energy/energy/industry-plastic?fbclid=IwAR2-AAuYRML-hMnUw644U7-6_aYuji_DzQ5RYVEP327JFF3NrS-9fDLcMAA.
[9] Piotrowska K, Kruszelnicka W, Bałdowska-Witos P, Kasner R, Rudnicki J, Tomporowski A, Flizikowski J, Opielak M.: "Assessment of the Environmental Impact of a Car Tire throughout Its Lifecycle Using the LCA Method" 2019 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6947500/.
[10] https://www.sciencedirect.com/science/article/abs/pii/0166309781900614.

For glass, for example, the total mass of glazing is the same in both types of vehicle. The components of this mass are shown in Table 7.1 (the mass of mirrors and the glass roof window are not included).

Table 7.1

Mass of glass in Peugeot 208

No.	Type of car windows	Number of car windows	Mass of a single car window
	-	-	kg
1.	Front	1	11,0
2.	Rear	1	4,3
3.	Front door	2	3,5
4.	Front bodywork	2	0,6
5.	Rear door large glass	2	2,6
6.	Rear door small window	2	1,3

Table 7.2

Results of the calculation of the energy consumption of the vehicle material groups – Peugeot 208 electric car

Peugeot e-208 Mass: 1105 kg (without battery)				
No.	Name of the material groups in the construction of the vehicle	Percentage share	Mass	Energy required to produce the material
	-	%	kg	kWh
1.	Steel, cast iron	68,0	787	21 249
2.	Non-ferrous metals	4,7	55	4 254
3.	Plastics	9,1	105	848
4.	Rubber	5,2	60	1 471
5.	Glass	3,2	37	308
6.	Liquids	5,1	60	b.d
7.	Other	4,7	54	b.d

Source: Zdonek B, Szypuła I.: Instytut Metalurgii Żelaza im. St. Staszica „Zmniejszanie emisji co2 w procesie elektrostalowniczym poprzez stosowanie alternatywnych materiałów nawęglających we wsadzie” – prace inż. 1, 2010; https://energyeducation.ca/encyclopedia/Aluminum; Leksykon naukowo-techniczny z suplementem. Warszawa: WNT, 1989. ISBN 83-204-0967-5. https://learn.openenergymonitor.org/sustainable-energy/energy/industry-plastic?fbclid=IwAR2-AAuYRML-hMnUw644U7-6_aYuji_DzQ5RYVEP327JFF3NrS-9fDLcMAA; Piotrowska K., Kruszelnicka W., Bałdowska-Witos P., Kasner R., Rudnicki J., Tomporowski A., Flizikowski J., Opielak M.: “Assessment of the Environmental Impact of a Car Tire throughout Its Lifecycle Using the LCA Method” 2019 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6947500/; https://www.sciencedirect.com/science/article/abs/pii/0166309781900614.

Table 7.3

Results of the calculation of the energy consumption of the vehicle material groups Peugeot 208 internal combustion car

Peugeot 208 Mass: 1158 kg				
No.	Name of the material groups in the construction of the vehicle	Percentage share	Mass	Energy required to produce the material
	-	%	kg	kWh
1.	Steel, cast iron	64,6	714	19 272
2.	Non-ferrous metals	6,7	74	5 763
3.	Plastics	9,5	105	848
4.	Rubber	5,5	60	1 471
5.	Glass	3,4	37	308
6.	Liquids	5,1	56	b.d
7.	Other	5,3	58	b.d

Different energy intensity values for the production of batteries for electric cars are available in the literature data. The cells of the Peugeot 208 electric vehicle are manufactured in the PRC by CAyTL.

The results of the LCA analyses of EV battery banks vary in the range of assumptions made, methodology and input data. The Li-Ion cells themselves (different cathode materials) adopted in the analyses are also different. The production of cathode materials and aluminium is the dominant contributor to CO2 emissions so producing Li-Ion batteries for an electric vehicle can result in emissions in the range of 56–494 kg of CO2 per 1 kWh of energy.

Table 7.4 shows publications in the literature (not older than 5 years) that describe the results of LCA analyses of CO2 emissions from battery production for electric vehicles.

Table 7.4

Results of LCA analyses of CO2 emissions related to the production of batteries for EVs

No.	Publication	Emissions from the production of battery
	-	kg CO2 e/ kWh
1.	Maarten Messagie, Vrije Universiteit Brussel, Transport & Environment	56
2.	Han Hao, Zhexuan Mu, Shuhua Jiang, Zongwei Liu, & Fuquan Zhao, Tsinghua University	96–127

continue table 7.4

3.	Mia Romare & Lisbeth Dahllöf, IVL Swedish Environmental Research Institute	150–200
4.	Wolfram P & Wiedmann T, Applied Energy	106
5.	Hanjiro Ambrose & Alissa Kendall, Transport and Environment	148–254 (without recycling) 194–494 (with recycling)
6.	Jennifer Dunn, Linda Gaines, Jarod Kelly, & Kevin Gallagher, Argonne National Laboratory	30–50
7.	Linda Ager-Wick Ellingsen, Bhawna Singh, & Anders Strømman, Environmental Research Letters	157 (Europe – use phase)
8.	Hyung Chul Kim, Timothy Wallington, Renata Arsenault, Chulheung Bae, Suckwon Ahn, & Jaeran Lee, Environmental Science & Technology	140
9.	Jens Peters, Manuel Baumann, Benedikt Zimmermann, Jessica Braun, & Marcel Weil, Renewable and Sustainable Energy Reviews	110
10.	Rachael Nealer, David Reichmuth, & Don Anair, Union of Concerned Scientists	73

Source: Kiełtyka A., Przemysł pojazdów EV w Polsce, praca inżynierska, Wydział Elektryczny Politechnika Śląska, Gliwice 2022; https://www.transportenvironment.org/publications/electric-vehicle-life-cycle-analysis-and-raw-material-availability; http://www.mdpi.com/2071-1050/9/4/504; http://www.sciencedirect.com/science/article/pii/S0306261917312539; Wolfram P, Wiedmann T.: Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity, Applied Energy, 2017, http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf; Ambrose H, Kendall A.: Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility, Transportation Research Part D: Transport and Environment, 2016, http://www.sciencedirect.com/science/article/pii/ S1361920915300390; http://www.anl.gov/energy-systems/publication/life-cycle-analysis-summary-automotivelithium-ion-battery-production-and; http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010; http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00830; http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.WWamKdNuJTY

The analytical results shown in Table 7.4 fall within a very wide range of values from 56 to 494 kg CO2 e/ kWh. It is therefore important to state the assumptions and boundary conditions used in the publications indicated in Table 7.4:

- It was assumed that a vehicle with a mass of 1200 kg and a 30 kWh battery travels 200,000 km in Europe. The actual electricity consumption of the vehicle analysed is 0,2 kWh/km. The result of the analyses: even in the EU countries with the highest CO2 emissions, EVs emit more than 25% less greenhouse gases into the atmosphere than diesel vehicles. The comparison of life cycle CO2 emissions of EVs after taking into account the energy mix in the energy system of the respective country (year 2017) is: Germany 119 g CO2/kWh, Italy 99 g CO2/kWh, Belgium 77 g CO2/kWh, Sweden 41 g CO2/kWh.

- The energy mix of China has been taken into account and cars with 20-30kWh batteries are operated in the USA. CO2 emissions associated with the production of components for the car have been taken into account. Batteries made in the US produce 65% less CO2 emissions than in the PRC.
- Results are shown for the ten most popular EVs in 2016 (including Tesla S 86 kWh, Nissan Leaf 23.8 kWh). It was assumed that EV car assembly consumes 350–650 kWh and battery production in the PRC. CO2 emissions were determined using a bottom-up analysis. The emissions of the elements used in the battery were calculated. Conclusions: energy for battery production accounts for at least 50% of the car's life cycle emissions.
- For an EV with a 42 kWh battery, it was assumed that it travels 150,000 km in its cycle and that the energy consumption during driving is 15 kWh/100km. The determined CO2 emissions were 351 g CO2/kWh. According to the authors, the production of a lithium-ion battery in the PRC can contribute to the emission of 317 g CO2/kWh battery.
- The research was conducted for EVs: Kia Soul 27 kWh, Fiat 500e 24 kWh, Honda FIT 20 kWh. The vehicle batteries analysed were manufactured taking into account the energy mix in the PRC.
- It uses a bottom-up analysis using the energy mix in the US for battery production.
- The authors modelled four vehicle sizes: small (17.7 kWh), medium (24.4 kWh), large (42.1 kWh) and luxury (59.9 kWh). The segments differed by the weight of the car and the maximum battery capacity that could be fitted to the car. The reports covered cars with 180,000 km mileage, would be used in Europe, where an average energy mix of 521 g CO2/kWh was assumed for the use phase.
- The study was based on data from a Ford Focus EV. The assessment was based on a compilation of materials and primary data from the battery industry. Conclusion: electric car production produces 39% more greenhouse gases than a comparable petrol or diesel car.
- The article provides an overview of LCA studies on lithium-ion batteries with a focus on the battery production process. Available studies in 2016 are summarised, followed by a comparison with actual data from industry and research institutions. Based on the results of the analysed studies, average values of the environmental impact of battery production are calculated.
- The report presents comprehensive results comparing global warming emissions from electric cars with their gasoline and diesel counterparts in the US.

Finally, for the purposes of our calculations, after a review of the literature data, we assumed an energy consumption for the production of Li-Ion cells for the Peugeot EV 208 vehicle of 47 kWh/kg, which for the entire vehicle battery gives a value of 16.5 MWh.

In the next calculation step, it was necessary to determine the CO2 emissions from the production of materials from a given material group. For this purpose, we assumed the simplification that all components of the car came from three locations: France and Slovakia and the Li-Ion cells that make up the battery of the electric vehicle were produced in the PRC. When calculating CO2 emissions, we used the annualised emissions of energy carriers in the energy mixes of the countries where the materials are produced. In this way, we determined the emissivity of the materials (CO2/kg) used to build the cars. In Table 7.5, we have shown the results of calculating CO2 emissions from the production of the main material groups. The simplifying assumption made is: production of materials and assembly of vehicles takes place in the EU (Slovakia and France) and the CATL battery is produced in PRC.

Table 7.5

Results of the calculation of CO2 emissions from the production of the main material groups of the electric and combustion vehicle

No.	Name of the material groups in the construction of the vehicle	CO2 emission – electric Peugeot e-208	CO2 emission – combustion Peugeot 208
	-	kg	kg
1.	Steel, cast iron	1041	1147
2.	Non-ferrous metals	331	230
3.	Plastics	46	46
4.	Rubber	79	79
5.	Glass	17	17
6.	Liquids	b.d	b.d
7.	Other	b.d	b.d

Source: Peters J., Baumann M., Zimmermann B., Braun J., Weil M.: The environmental impact of Li-Ion batteries and the role of key parameters – A review, Renewable and Sustainable Energy Reviews, 2017 http://www.sciencedirect.com/science/article/ pii/S1364032116304713

The final step in the LCA analysis related to the production phase is the consideration of energy consumption and CO2 emissions during the final assembly of the vehicles. Based on the literature, the final assembly process of a car on a production line consumes about 1.5 MWh of energy[11]. We assumed that 50% of this energy value comes from renewable energy sources. The assembly process includes the shaping of steel and aluminium components, welding and sealing of metal parts of the car, bolting of

[11] https://alebank.pl/fabryki-aut-coraz-bardziej-zielone/?id=16653&catid=361.

components, painting, assembly of components, quality testing. There are several activities in the assembly process that are different for both types of vehicles. In spite of the obvious differences in the construction of the propulsion systems, the assembly of the powertrain of both vehicles is very similar. The internal combustion engine or electric motor is connected to the body in the so-called "wedding" process, which consists in lifting the pre-assembled unit: the engine and its accessories, transmission, half-shaft by the wheels together with the suspension and steering systems to the top, where the unit is bolted to the body. The energy consumption for this process can be assumed to be the same. In electric cars, a battery is additionally mounted, but this is done in a similar way to "wedding" and the energy for this process is the same as the assembly of additional assemblies (e.g. exhaust system or radiators) in the case of a combustion engine. It was therefore assumed that the process of assembling the aforementioned non-standard components in an electric car consumes the same amount of electric energy as in a combustion car. The summary results of energy consumption and related CO2 emissions are shown in Fig. 3.

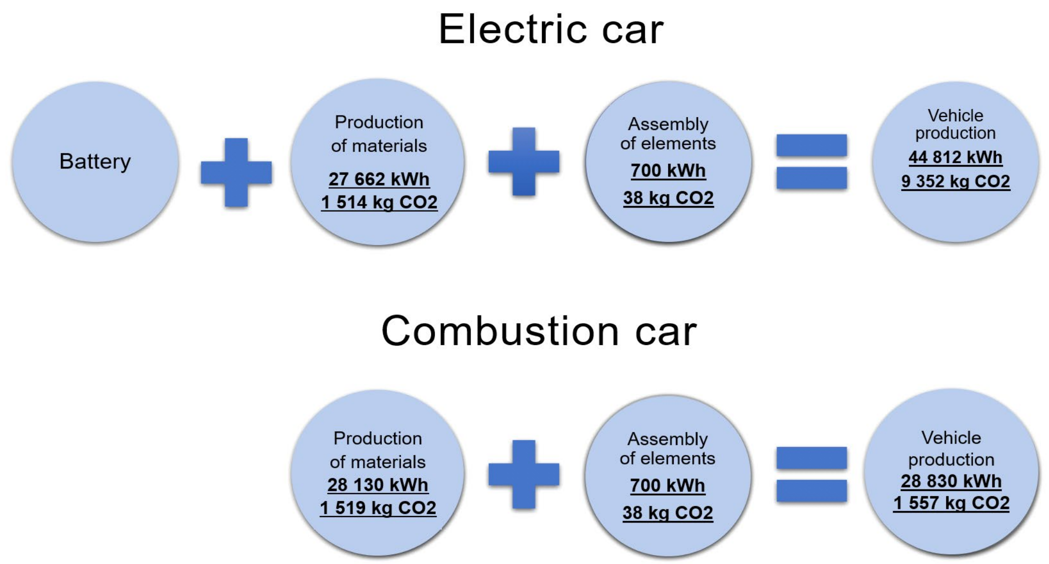

Fig. 7.3. Energy consumption and CO2 emissions - material production and car assembly phase
Rys. 7.3. Zużycie energii i emisja CO2 - produkcja materiałów i faza montażu samochodu

Another area of calculation was the operation of both vehicles. In the analysis, we made the obvious assumption that both vehicles are driven in the same driving cycles. For the calculation of CO2 emissions, the source and method of obtaining energy to power the vehicles is crucial here. The calculations took into account:

- the actual energy consumption of both vehicles,
- the efficiency of the energy system and batteries,
- the efficiency of the oil extraction process and of its transport to the filling station.

It has been calculated that for an electric car, when the above factors are taken into account, for every 10kWh of energy consumption, the CO2 emission is 8.8 kg, while for an internal combustion car, every 10kWh of energy consumption is associated with the emission of 12.2 kg of CO2. The energy consumption and CO2 emissions during operation for up to 200,000 km are shown in Figures 4 and 5. Disposal for both vehicles will consume a similar amount of energy and the difference will occur when disposing of the batteries, which has been taken into account in the calculations.

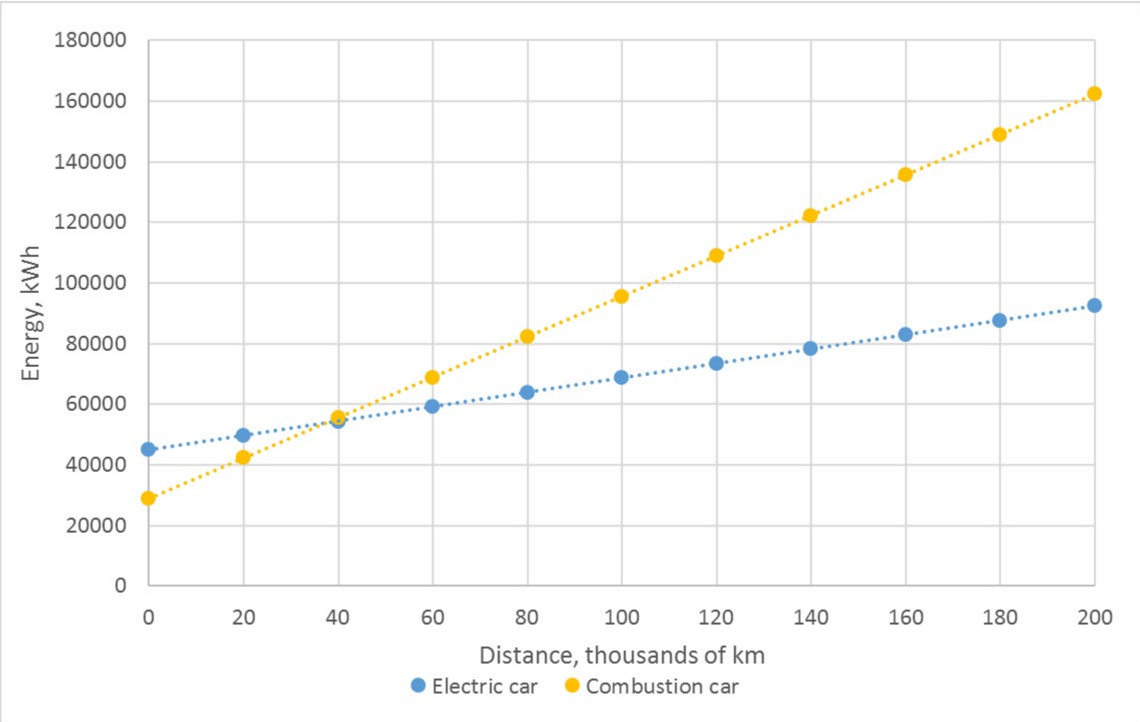

Fig. 7.4. Energy consumption – car use in Poland
Rys. 7.4. Zużycie energii – użytkowanie samochodów w Polsce

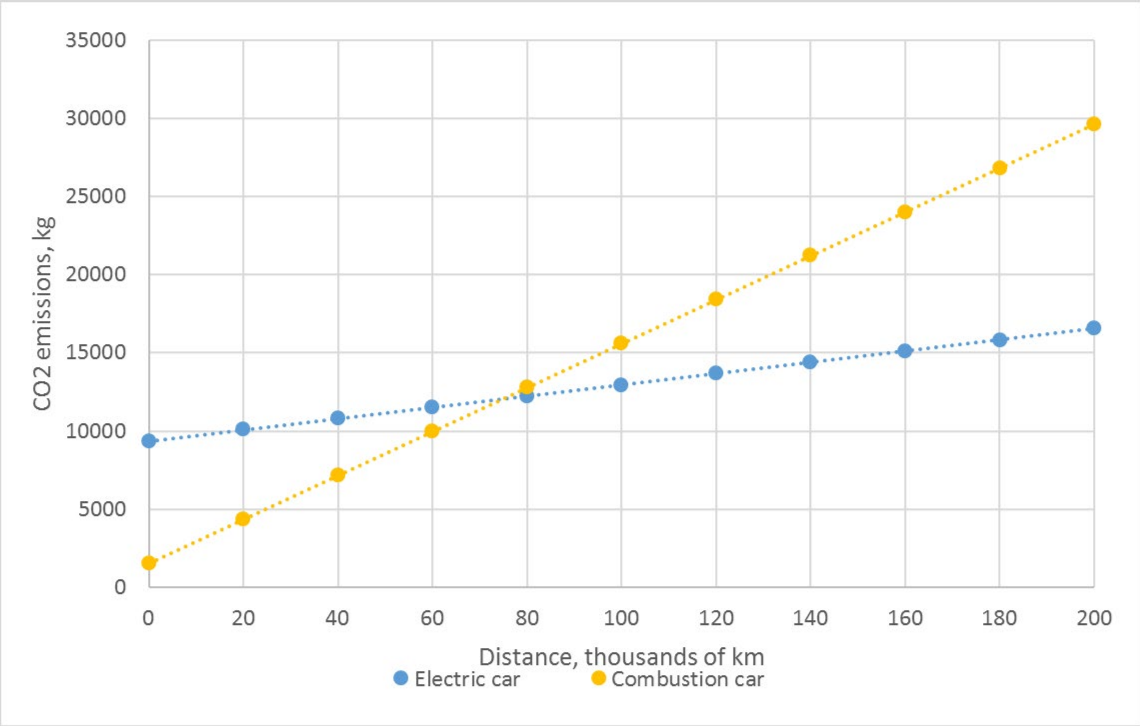

Fig. 7.5. CO_2 emissions – car use in Poland
Rys. 7.5. Emisja CO_2 – użytkowanie samochodów w Polsce

7.3. Key conclusions

Our analysis showed that:

- the energy input to produce an electric car about 1.6 higher than its combustion counterpart,
- battery production accounts for a significant proportion of the energy consumption during vehicle manufacture, so it is beneficial to transfer the production of cells in PRCs to countries with emission factors of the energy mix below 200 g/kWh,
- our analysis did not include processes of capacity recovery in batteries (e.g. after reaching SOH=80%), which will significantly reduce energy consumption Such services will probably appear for Li-Ion cells in a few years (analogically to commonly used such methods for lead-acid cells),
- the current crisis in the EU car market will probably accelerate the trend to establish factories for refurbishing used cars and selling them back to the market. This will reduce the negative impact of motoring on the environment,

- in the case of the energy mix in Poland, the advantage of the EV in terms of CO2 emissions will occur after 120 000 km. In other EU countries it will happen much sooner (e.g. in Germany after 80,000 km, in France after 60,000 km),
- the calculations did not take into account that the vehicles are assembled in factories with zero grid energy consumption (e.g. balancing by PV)-this will significantly improve the carbon balance of production.

DOI:10.34918/87428

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8. MODELLING, CONTROL AND DIAGNOSTICS OF SUSPENSION FOR AN OFF-ROAD VEHICLE WITH MAGNETORHEOLOGICAL DAMPERS

8.1. Introduction

Driving safety and ride comfort will remain a constant and important need for modern mobility when designing a road or off-road vehicle. Such key factors are always valid when moving on the ground along a given trajectory. They are and will be especially important in less industrialized areas where individual means of transport have significant advantages over limited public means. Furthermore, acceptable vehicle handling and adhesion of wheels to the road surface will support the reliability of autonomous driving. It is especially challenging in areas with limited road quality and limited access to the electronic database of road maps. Finally, electronically controlled and electrically supplied suspensions can take advantage of mobile energy resources, which are much more easily available in the case of currently widely developed electric cars.

The driving safety and the ride comfort are contradictory; e.g. in the case of the typical passive suspension the improvement of driving safety causes degradation of ride comfort. On the one hand, the acceptable driving safety, which is more closely analyzed as vehicle handling or road holding, allows the vehicle to stick to the road and consequently the driver to reach destination of the journey. On the other hand, adequate ride comfort is often related to the health of the vehicle passenger, for example, when discussing the mitigation of road-induced vibration that propagates through to the vehicle body and influences human bodies. Therefore, during the vehicle design phase, the appropriate suspension parameters are selected that are a compromise between driving safety and ride comfort depending on the target operating conditions of the

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vehicle. Furthermore, electronically controlled suspensions are being developed and integrated with the autonomous vehicle control system, which allows us to better adapt to varying road conditions.

The presented study is related to methods of suspension modelling, control and diagnostics applied for an experimental all-terrain vehicle with MR dampers. The main goal of the research is to demonstrate methods of online observation of the behavior of shock-absorbers during vehicle exploitation. The article also presents approaches to the development of signal processing algorithms dedicated to early detection of suspension failures. The study is divided into four sections. The introduction and state-of-the-art related to the presented topic are reported in Section 1. The Section 2 describes the experimental vehicle and suspension control system. It reports methods of suspension modelling and it presents experiments carried out for the vehicle based on the diagnostic station and in terrain. In the Section 3 results and their analysis are presented for measurements obtained in selected cases. The main remarks presented in the article are concluded in Section 4.

8.1.1. Assessment of driving safety and ride comfort

Off-road vehicles are especially prone to deteriorated ride comfort and frequent loss of road adhesion. Their specific physical parameters, e.g. higher center of gravity, degradate vehicle handling and such parameters lead to extensive vehicle body pitching and rolling compared to typical road vehicles. Thus, researchers frequently analyze the factors mentioned above for off-road vehicles and try to find the best compromise[2]. As a consequence, the optimized settings of suspension of off-road vehicles are analyzed depending on different roughness of road and varying vehicle speeds[3] or with respect to different driving manoeuvres[4] .

Ride comfort is commonly assessed based on the root mean squared value of acceleration[5]. Furthermore, the comparison of objective methods for ride comfort can lead to the statement that the vertical direction of measurement is dominant[6]. Vibrations

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that affect passengers in vehicles are commonly analyzed up to 25 Hz, but are particularly dangerous when they overlap with resonance frequencies of the human body[7].

Vehicle handling, which is related to driving safety, can be evaluated for steady-state response when the vehicle moves along the constant radius circle or for transient response when driving test maneouvres are analyzed[8]. In relation to vehicle body motion, handling can be analyzed based on the roll angle[9] and the roll rate[10] when predicting vehicle rollover, or the pitch angle can be taken into account[11]. The road holding determines to what extent the tire adjusts to the road surface. It requires optimized inflation or, consequently, deflection of the tire. Any deviation from nominal inflation[12] or deflection of the tire deteriorates its adhesion to the road surface. Thus, dynamic tire deflection is the main quantity connected with road holding that can also be degraded by wheel resonance.

8.1.2. Modelling of vehicle suspension

The analysis of suspension and its influence on vehicle dynamics and vibration is commonly based on the assumption that the vehicle behaves as a vibrating mechanical system. Complex vehicle models are defined as multi-body models consisting of a finite number of rigid elements where each element is connected to the other using stiffness and damping components[13]. Here, a model of an articulated frame-steered vehicle including hydro-pneumatic suspension was prepared as three-dimensional multi-body model in ADAMS simulation environment coupled with selected subsystems described in Matlab/Simulink.

The complexity of vehicle models is generally defined by the number of described DOFs (degrees of freedom). Models described at the lowest complexity are often used

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in analytical analysis and as a simplification of vehicle integrated in control algorithms. Complex models allow for more sophisticated simulations but require their numerous parameters to be properly estimated, and such models are computationally demanding.

A quarter-car, which describes the vertical motion of a selected part of the vehicle, is still applied in many studies presented in the literature[14]. It generally consists of two masses representing the quarter vehicle body and a wheel, as well as it additionally includes a set of dampers and springs corresponding to the quarter vehicle suspension and the tire.

In many cases, the vehicle model is extended to half-car or full-car models. The half--car model exhibits 4 DOFs, three of which describe vertical motion of the vehicle body and two unsprung masses. The fourth DOF corresponds to vehicle body pitch angle[15] or roll angle[16] depending on whether the model is intended to map pitch or roll dynamics of the vehicle, respectively.

The full-car model offers an additional dimension for which vibrations of the vehicle are described. As a result, a 7 DOFs model is commonly obtained where the vehicle body exhibits 3 DOFs, i.e. heave, pitch and roll angle, and additionally the vertical motion of each wheel is mapped[17]. Furthermore, additional components can also be included in models such as passenger seats[18] or vibration models of human bodies of passengers[19].

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8.1.3. Control of vehicle suspension

The need to adapt suspension parameters and vehicle dynamics to varying vehicle parameters, e.g., its load, and road conditions, promotes development of adaptive, electronically controlled suspension. Active and semi-active suspension can be distinguished where, in general, the former is characterized by the possibility of adding energy to the vibrating system. The latter is based on changing parameters of the suspension during the ride and it is preferred for low energy consumption.

Three types can be distinguished in the group of active suspensions[20] where load-leveling suspensions can be treated as quasi-active with an actuation bandwidth significantly below the dominant suspension resonance. The latter two active configurations, i.e. slow-active or fully-active, differ with an actuation bandwidth which is between body and wheel resonance or cover full suspension dynamics, respectively. Active suspension can be commonly based on three types of actuators, i.e. hydraulic[21], pneumatic, electromagnetic[22] or it can be a hybrid solution[23].

Currently, available semi-active suspensions are mainly based on semi-active dampers, and they can be divided into solutions with slowly- or fast-modified damping ratio. Slow-semi-active systems are generally made with an open-loop architecture[20] when a driver has the option of manually switching between several levels of suspension damping. The fast-semi-active suspension operates in closed-loop configuration based on measurement signals taken from sensors located in the vehicle and tracking its motion.

For both above-mentioned variants of semi-active suspension, three types of semi-active dampers can be used, i.e. magnetorheological[24], servo/solenoid-valve[25] and electrorheological[26] where the former two are more common. The MR (magnetorheological) damper consists mainly of a cylinder and a piston[27]. It is filled with an MR fluid thatincludes magnetizable particles suspended in an oil. While the piston moves, MR fluid flows through piston gaps in the vicinity of built-in electric

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coils[28]. Particles of MR fluid subjected to magnetic field induced by supplied electric coils reorganize in chainlike structures and they obstruct the flow of MR fluid through piston gaps. On a macroscopic scale, it results in a change of the damping parameter of the MR damper. Contrary to MR dampers, in the case of solenoid/servo-valve dampers oil flow through the damper and consequently the damping parameter is adjusted using a bypass solenoid/servo valve commonly attached to the outer tube of the damper[25]. Similarly to the MR damper, the servo-valve damper can be applied for numerous drivingsafety-related tasks, e.g., in an active anti-roll bar control of a heavy vehicle[29].

8.1.4. Diagnostics of vehicle suspension

Diagnostics of vehicle suspension is crucial in order to maintain the proper state of suspension, and consequently acceptable driving safety and ride comfort. Different approaches to suspension diagnostics can be grouped into stationary and driving methods, where the former are commonly used[30]. Stationary methods are divided into free vibration methods and forced vibration methods[31]. In the case of free vibration, a damping ratio is evaluated based on a number of half-periods of the vibration but vertical force generated by the tire on the ground can additionally be measured and analyzed.

Forced vibration methods are generally applied in a stationary suspension diagnostic station where the vehicle wheel is initially subjected to vibration of 16–25 Hz generated by a mechanical exciter. Then, the occurrence of suspension and wheel resonances is assessed when the exciter gradually reduces the frequency of excitation[31]. BOGE and EUSAMA diagnostic methods are distinguished, which differ in the type of the analyzed quantity describing the vibrations. In the case of BOGE, a peak-to-peak value of vertical wheels displacements of the vibration plate is analyzed while EUSAMA method is based on measurements of wheel load mainly taken when resonance occurred[32].

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Mobile suspension diagnostics systems installed in a vehicle are an interesting alternative to stationary ones. They take advantage of sensors installed in vehicles by default, e.g. accelerometers, or they can additionally use other sensors, e.g. suspension deflection or force sensors in order to enhance quality of suspension monitoring. A study of vehicle dynamics for different parameters of suspension allows to correlate the latter with ride comfort, road handling, and stability of the car[33]. An example of a suspension diagnostic method applied to a railway vehicle takes advantage of vibration acceleration measurements related to a road profile and a vehicle body[34].

Another method was applied for a full vehicle model and was dedicated to an oil leakage of an automotive magnetorheological damper. Two approaches of online estimation of suspension transmissibility were proposed based on the force or accelerometer sensor[35]. Semi-active shock absorber can also be monitored using an observer-based approach or a method based on parameter identification[36]. The presented fault detection methods can not only be used to warn the driver about suspension failure, but they can also be applied for fault-tolerant control reconfiguration integrated with a semi-active suspension control algorithm[37].

8.2. Material and methods

The proposed configurations of adaptive suspension are demonstrated for the experimental all-terrain vehicle equipped with suspension MR dampers. Different signals are generated during experiments using a dedicated measurement and control system installed in the vehicle, These signals are further processed and analyzed in the time and frequency domain within the presented study. The following validation methods are distinguished: simulation research applied using the dynamic model of vehicle suspension, laboratory experiments performed using the suspension diagnostic station, and tests carried out in terrain using the test route.

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[33] Hamed M., Tesfa B., Gu F., Ball A. D.: A study of the suspension system for the diagnosis of dynamic characteristics. 2014 20th International Conference on Automation and Computing, 2014, pp. 152–157.
[34] Sakellariou J.S., Petsounis K.A., Fassois S.D.: Vibration based fault diagnosis for railway vehicle suspensions via a fuctional model based method: a feasibility study. Journal of Mechanical Science and Technology, 2015, Vol. 29, pp. 471–484.
[35] Lozoya-Santos J.J., Tudon-Martinez J.C., Morales-Menendez R., Ramirez-Mendoza R., Garza-Castanon L.E.: A fault detection method for an automotive magneto-rheological damper. IFAC Proceedings Volumes, 2012, Vol. 45, No. 20, pp. 1209–1214.
[36] Hernandez-Alcantara D., Morales-Menendez R., Amezquita-Brooks L.: Fault detection for automotive shock absorber. Journal of Physics: Conference Series, 2015, Vol. 659, No. 1, 012037.
[37] Basargan H., Mihaly A., Gaspar P., Sename O.: Fault-tolerant semi-active suspension control for degradation in damper performance. MED 2021 – 29th Mediterranean Conference on Control and Automation, Jun 2021, Bari (virtual), Italy.

8.2.1. All-terrain vehicle with adaptive suspension

The considered ATV CF500-2A off-road vehicle presented in Figure 8.1 is 2.3 meters long, 1.2 meters wide and 0.9 meters high. It is equipped with a 4-stroke-1-cylinder petrol engine and 4-wheel drive. The original shock absorbers of the vehicle were replaced by MR dampers, and a dedicated control system was installed in the vehicle. The system is mainly responsible for the generation of control signals dedicated to MR dampers. It takes advantage of numerous sensors installed in the vehicle, i.e. accelerometers located in the vehicle body and in the vicinity of each wheel, suspension deflection sensors dedicated to each part of the suspension, and a force sensor measuring force generated in the front left suspension column.

The above mentioned sensors are mainly used for the presented study. However, others are additionally available for extended experiments. The IMU (inertial measurement unit) module is located under the driver's seat and it includes acceleration, gyroscope and magnetometer. Four Hall-effect sensors are located in the vicinity of each wheel and are responsible for measurements of wheel angular velocities. Furthermore, additional accelerometers can be connected to the measurement unit, and they allow for measurement of acceleration of the handle bar or footrest.

Fig. 8.1. Experimental off-road vehicle with MR dampers and suspension control system
Rys. 8.1. Eksperymentalny pojazd terenowy z tłumikami MR i systemem sterowania zawieszeniem
Source: Own photo, 2017.

8.2.1.1. Measurement and control system

The measurement and control system installed in the experimental vehicle is organized in several control layers and it consists of numerous devices as presented in the block diagram in Figure 8.2. Peripheral MCUs (measurement and control units) are responsible for direct communication with acceleration and wheel speed sensors. Such measurement data are further transferred via the CAN bus to the main suspension controller which is based on a multiple-core single board computer. The main controller processes available measurement data, executes implemented control algorithms, and it generates values of control signals which are desired electric currents supplying MR dampers. The control signals are transferred back to peripheral units and used for MR damper control.

Apart from MCUs, other units such as an IMU module or an additional measurement controller communicate with the main controller via RS232 protocol or CAN bus, respectively. The measurement controller allows the acquisition of signals obtained from LVDT suspension deflection sensors and the force sensor. Finally, the main suspension controller is supervised via WiFi connection by a human operator using the supervisory unit. Such a wireless configuration simplifies conducting experiments in terrain.

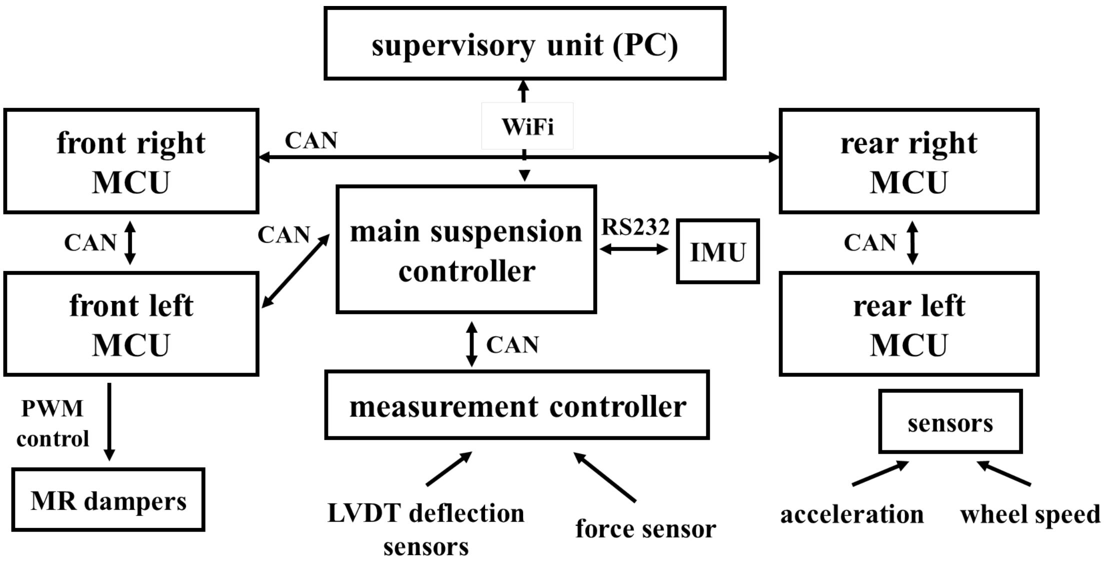

Fig. 8.2. Block diagram of the measurement and control system of the experimental off-road vehicle
Rys. 8.2. Schemat blokowy systemu pomiarowo-sterującego eksperymentalnego pojazdu terenowego
Source: Own elaboration.

2.1.2. Suspension magnetorheological damper

Construction of the MR damper is similar to a classical shock-absorber, it consists of a cylinder and a piston with gaps. The suspension MR damper installed in the experimental off-road vehicle using a dedicated mechanical adapters is presented in Figure 8.3.

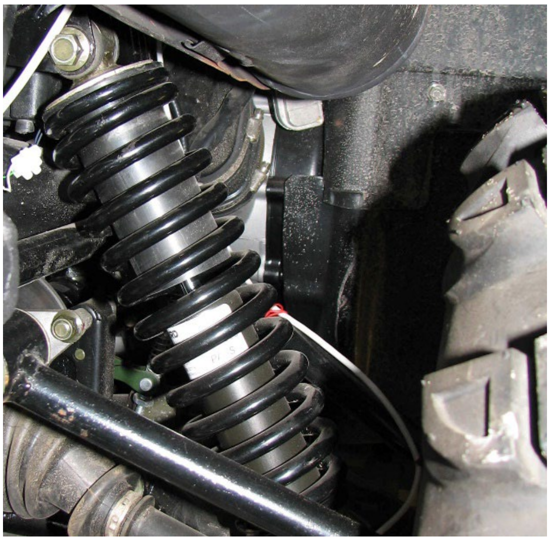

Fig. 8.3. A shock-absorber with MR damper installed in the experimental off-road vehicle
Rys. 8.3. Amortyzator z tłumikiem MR zamontowany w eksperymentalnym pojeździe terenowym
Source: Own photo.

Contrary to classical shock-absorbers, the MR damper is filled with MR fluid, which consists of magnetizable particles suspended in oil. Furthermore, the piston of the MR damper includes built-in electric coils, which induce magnetic field when supplied with electric current. Such particles reorganize in chain-like structures when flowing through these piston gaps subjected to a magnetic field.

Varying control current influences the damping characteristics of MR damper in a macroscopic scale, allowing for fast modification of suspension damping parameters during vehicle ride. Exemplary results obtained for the MR damper subjected to sinusoidal displacement excitation generated by an MTS experimental setup are presented in Figure 8.4. The damper piston was moving with an amplitude equal to 25 mm and a frequency equal to 2.0 Hz.

During experiments the temporary constant values of control current were varying in range from 0 to 1 ampere, which resulted in a group of force-velocity characteristics presenting a dissipative domain of the MR damper, i.e. a range of damper forces achievable for each value of piston velocity. They mainly cover only two quadrants of the force-velocity coordinate system, which is characteristic for semi-active dampers. Such characteristics obtained for control currents equal to 0.05, 0.15 and 0.5 amperes are presented in Figure 8.4. It can be noticed that force generated by MR damper exhibits force saturation for greater piston velocities, and additionally hysteresis loops are visible in these force-velocity characteristics.

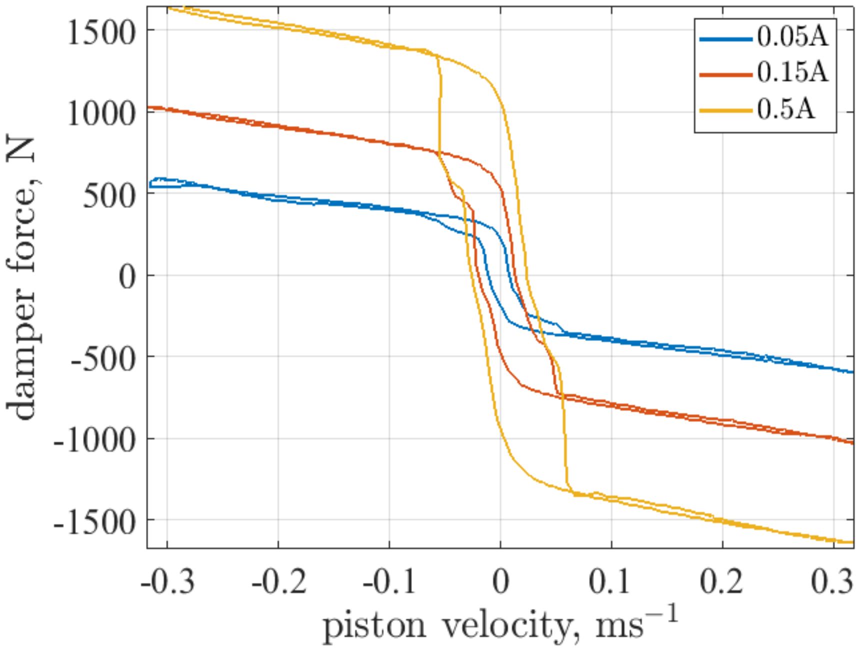

Fig. 8.4. Force-velocity characteristics of MR damper for different control currents
Rys. 8.4. Charakterystyka siła-prędkość tłumika MR dla różnych prądów sterujących
Source: Own elaboration.

8.2.2. Methods

The procedure commonly applied for validation of control algorithms in the case of presented experimental vehicle consists of three phases: simulation-based studies, laboratory experiments, and tests in terrain. Laboratory experiments are carried out after the simulation phase using a dedicated suspension diagnostic station. The validated measurement and control system including the implemented algorithms, is finally tested during off-road driving. Additionally, for some cases, a hardware-in-the-loop approach is used where the target controller including implemented algorithm communicates with another computational unit which emulates measurement and control system of the actual vehicle.

8.2.2.1. Suspension diagnostic station

The experimental setup dedicated to diagnostics of vehicle suspension is located in a laboratory in the Faculty of Energy and Environmental Engineering at the Silesian University of Technology, as presented in Figure 8.5. It consists of a right and a left mechanical exciter that are driven by electric motors rotating an eccentric shafts. The eccentric shaft of each exciter is connected to the exciter's steel plate through an elastic steel connector that functions as a spring element.

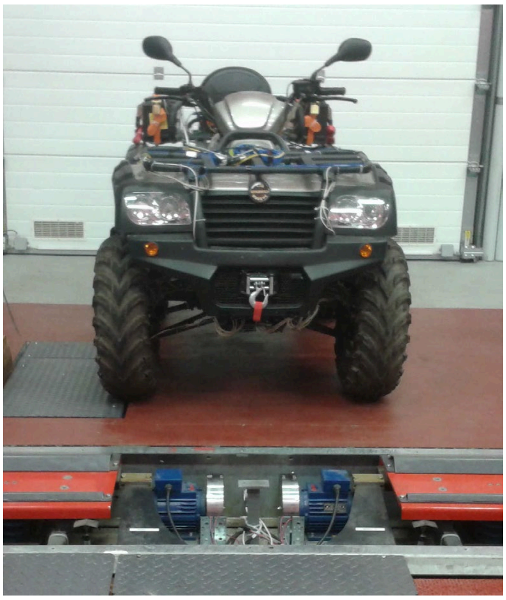

Fig. 8.5. Experimental off-road vehicle and laboratory setup for suspension diagnostics
Rys. 8.5. Eksperymentalny pojazd terenowy i stanowisko laboratoryjne do diagnostyki zawieszenia
Source: Own photo.

Classical diagnostic stations allow for the operation of only one mechanical exciter at the same time. However, it was inferred from the preliminary analysis that, in the case of the experimental vehicle, it is required to subject at least two front or rear wheels to vibration excitation. Thus, the control system of the diagnostic station was modified among others by adding two inverters and motor rotation sensors, which allowed for a smooth change of motor operation frequencies. Furthermore, a higher layer of the motor controller was implemented based on the microcontroller system in order to maintain predetermined synchronization between the exciters. The fact of in-phase or out-of-phase synchronization of the right and the left vibration excitation signals has decisive influence on the response of the vehicle since depending on such synchronization the heave (vertical) or roll (angular) components of the resultant excitation can be dominant.

8.2.2.2. Off-road test area

The final experiments of the suspension control system are carried out on a test route in terrain in Gliwice town near the university campus, as presented in Figure 8.6. The test route of an approximate length of 900 meters was marked while maintaining a few requirements, such as sufficient unevenness of the road surface which allows for sufficient excitation of vehicle vibration. For safety reasons, limited and preferably no pedestrian and vehicle traffic on the test route is strongly recommended. The test route studied in the presented manuscript also included several speed bumps. As a result, a complete set of vehicle vibration sources can be used for control algorithm validation where sinusoidal vibration excitation can be generated by the diagnostic station, the single impulse excitation is generated when driving over the speed bands, and wideband road-induced vibration are generated when driving on irregularities of the test route.

Fig. 8.6. Test route marked out in Gliwice for off-road driving of the experimental vehicle
Rys. 8.6. Droga testowa wytyczona w Gliwicach dla jazd terenowych pojazdu eksperymentalnego
Source: Google Maps.

8.2.2.3. Dynamic model of vehicle suspension

Simulation-based studies are low-cost and represent a key phase of the validation process of the measurement and control systems. Different approaches to modelling of the presented experimental vehicle were applied within the framework of previous research studies, such as quarter-car, half-car or full-car models. The mechanical representation of the latter, which takes into account 7 degrees of freedom in its basic version, is presented in Figure 8.7. The presented model is a connection of masses, springs, and dampers corresponding to parameters of the vehicle body, suspension, wheels, and tires. Motion of the vehicle body is described using 3 degrees of freedom corresponding to its heave, pitch, and roll angles. Further, 4 degrees of freedom describe vertical motion of each wheel.

Dynamics of the implemented full-car model can be described using different approaches such as Euler-Lagrange equations or balances of forces and moments of forces. Simulation results presented in the given manuscript were obtained for a full-car model mathematically derived within the framework of the previous study[38].

[38] Krauze P., Kasprzyk J.: FxLMS control of an off-road vehicle model with magnetorheological dampers, [in:] Bartoszewicz A., Kabziński J., Kacprzyk J. (eds.): Advanced, Contemporary Control. Advances in Intelligent Systems and Computing. Springer, Cham 2020, Vol. 1196, pp. 747–758.

Additionally, this dynamic vehicle model can be extended by different components, also described as a vibrating mechanical system and related to passengers and their human bodies, or extended by a model of mechanical exciters used in the diagnostic station. Furthermore, elastic properties of rubber holders of shock absorbers installed as part of the suspension of the experimental vehicle can be taken into account in this vehicle model.

Special attention should be paid to the description of the behavior of MR dampers. Force-velocity characteristics presented in Figure 8.4. can be mapped assuming different complexity starting from the Bingham model which includes the Coulomb dry friction force and viscous damping components. Further extensions of MR damper model can be constituted as complex mechanical systems including sets of masses, springs, and dashpots such as the Gamota-Filisko model[39]. Further modelling approaches take into account the application of the hyperbolic tangent function or Bouc-Wen hysteresis component as presented in the Bouc-Wen model[40].

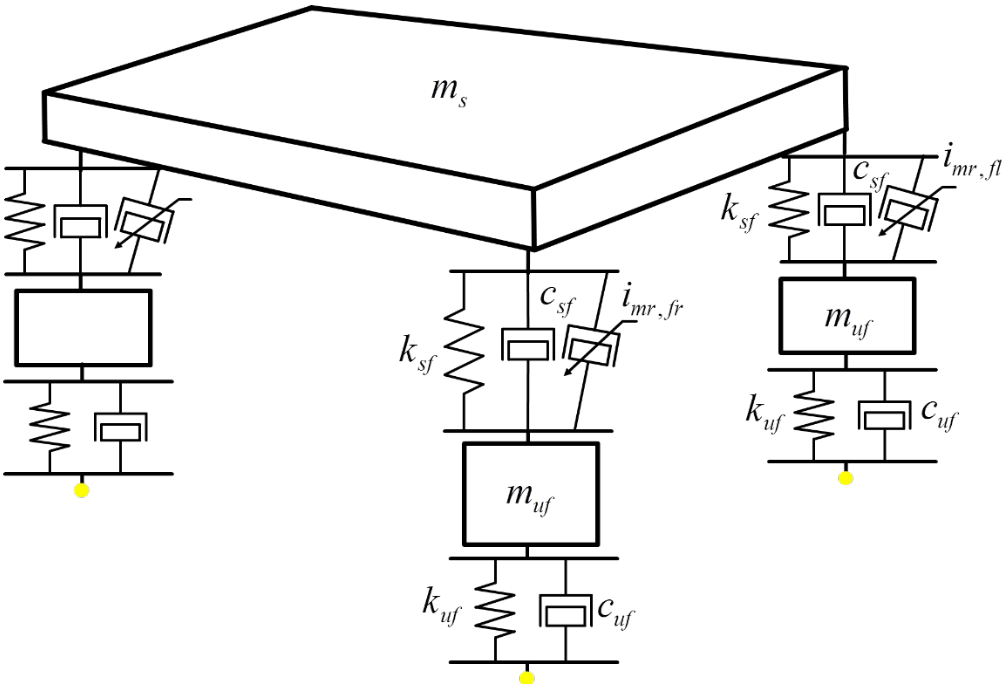

Fig. 8.7. Mechanical representation of vehicle model with 7 degrees of freedom
Rys. 8.7. Mechaniczna reprezentacja modelu pojazdu o 7 stopniach swobody
Source: Own elaboration.

[39] Gamota D.R., Filisko F.E.: Dynamic mechanical studies of electrorheological materials: moderate frequencies, Journal of Rheology, 1991, Vol. 35, pp. 399–425.
[40] Ogonowski S., Krauze P.: Trajectory control for vibrating screen with magnetorheological dampers, Sensors, 2022, Vol. 22, No. 4225, pp. 1–33.

The transmissibility frequency characteristics are used for the analysis of how vibrations propagate and how this propagation is controlled in vibrating mechanical systems. In the case of vehicles, the transmissiblity is commonly evaluated for a signal path from road-induced excitation to vibration of wheels or selected modes of vibration of the vehicle body[38]. For the purpose of the presented study, transmissibility frequency characteristics was evaluated for the front suspension in order to demonstrate the influence of increased suspension damping on vibration propagation, as presented in Figure 8.8. It can be noticed that the vehicle model with low suspension damping, denoted as c_s, exhibits a single resonance peak at a frequency close to 2 Hz. However, for increasing suspension damping, the resonance peak is shifted to a frequency range close to 6 Hz. This phenomenon can be explained by the fact that in the case of low suspension damping, vibration of the vehicle body is determined mainly by the stiffness and damping of the suspension. However, high values of suspension damping parameters result in coupling of the wheels and vehicle body masses and, as a consequence, stiffness and damping of tires become dominant for vehicle body vibration.

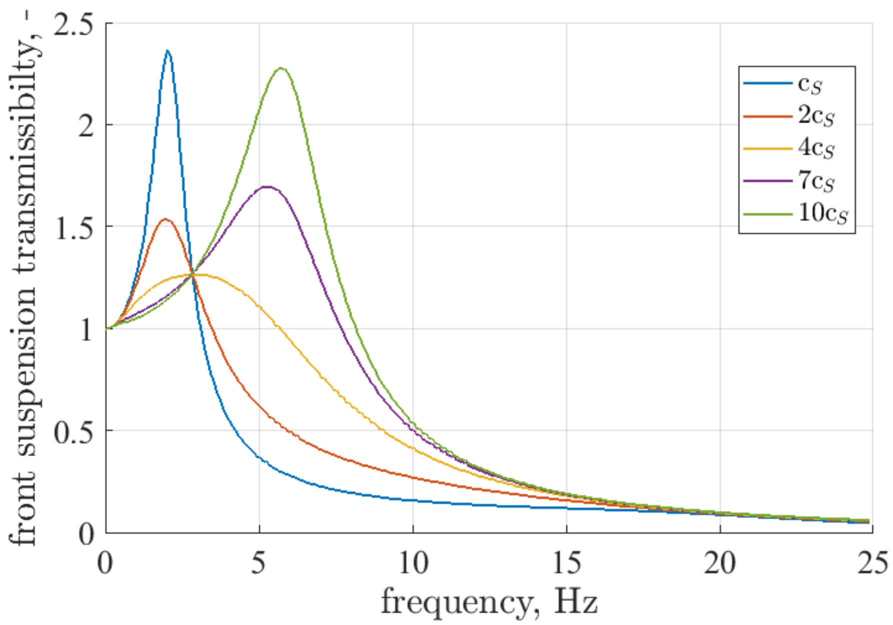

Fig. 8.8. Comparison of transmissibility characteristics of the front vehicle body part of the vehicle model with 7 degrees of freedom for increasing suspension damping parameter

Rys. 8.8. Porównanie charakterystyk współczynnika przenoszenia drgań przedniej części nadwozia modelu pojazdu o 7 stopniach swobody dla wzrastającego parametru tłumienia zawieszenia

Source: Own elaboration.

8.3. Results

The experimental results presented in the manuscript were evaluated based on measurement data obtained from several sensors installed in the vehicle. The vertical motion of the vehicle body was tracked using accelerometers located in its front right and left parts. The deflection of the front vehicle suspension was analyzed using LVDT sensors. The force generated in the front left suspension column was measured using force sensors built into the shock absorber holder.

The majority of the measurement data, especially in the case of driving tests in terrain with vehicle engine running, were preprocessed using a lowpass filter with cut-off frequency equal to 25 Hz in order to avoid additional measurement disturbances not directly related to the vehicle and suspension dynamics. Selected measurement signals were additionally filtered using a highpass filter to exclude signal offset and drift.

The final analysis was carried out in the time and frequency domains. Experiments were conducted for different values of control currents and compared in time diagrams, where differences in amplitudes obtained for different cases could be pointed out. In the case of experiments conducted using diagnostic station, the transmissibility frequency characteristics was obtained. Furthermore, the dynamics of the experimental vehicle was also analyzed in the frequency domain using power spectral density characteristics evaluated based on measurement data obtained from driving tests performed on the off-road test route.

8.3.1. Suspension diagnostic station

Laboratory experiments were conducted for consecutive excitation frequencies where each frequency is accompanied by a startup phase, stabilization of exciter frequency, phase of proper measurements, the stop phase and a period of time for the motors to slightly cool down. Procedure of such tests can be visible in time diagrams of suspension deflection, force and vehicle body acceleration presented in Figures 8.9–8.11 obtained for suspension MR dampers operating with zero control current and control current equal to 0.2 ampere.

Measurements of suspension deflection indicate that its amplitude decreases significantly with increasing suspension damping caused by increasing damper control currents. On the other hand, time diagrams of suspension force show that for 0.2 ampere its amplitude can increase from approximately 100 N to 1 kN. Figure 1.11 presenting the vertical acceleration of the vehicle body confirms that for greater control currents, the vehicle body is subjected to greater accelerations.

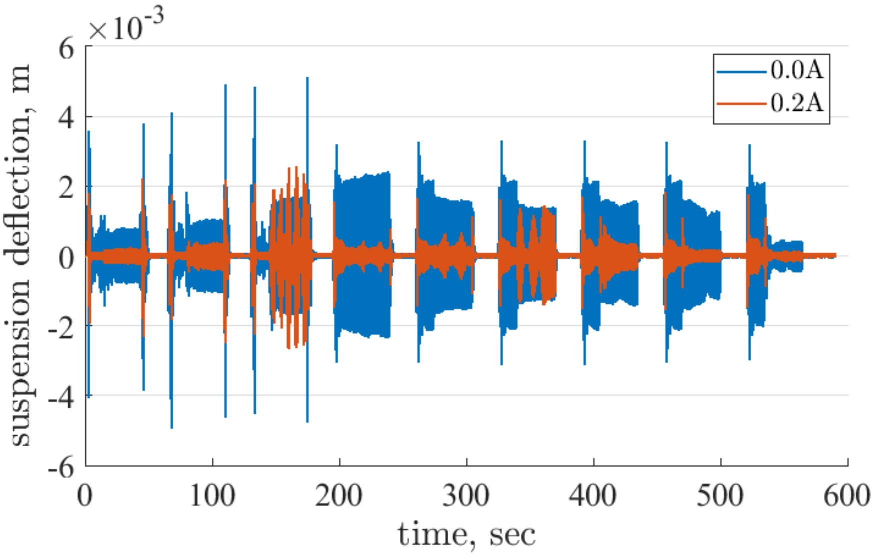

Fig. 8.9. Comparison of time diagrams of front left suspension deflection for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.9. Porównanie przebiegów czasowych ugięcia przedniego lewego zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

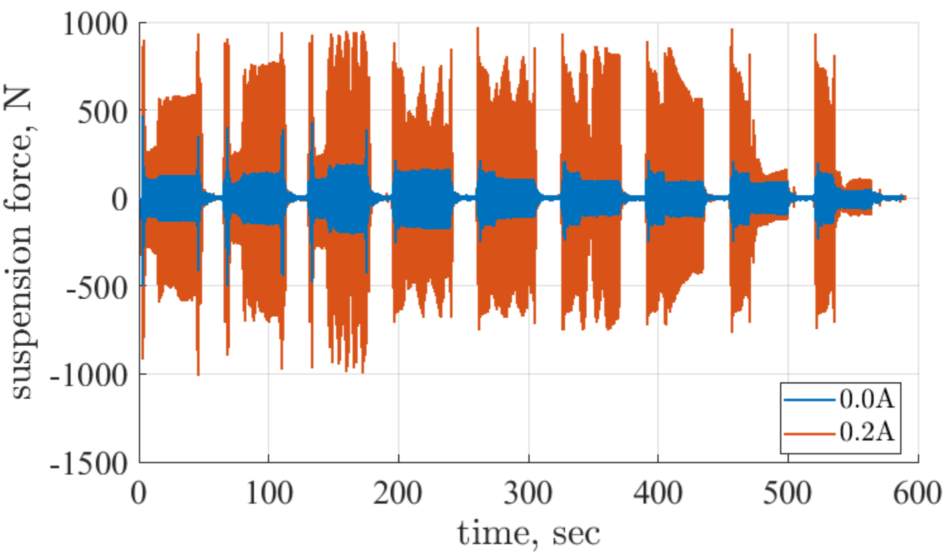

Fig. 8.10. Comparison of time diagrams of force generated in the front left suspension column for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.10. Porównanie przebiegów czasowych siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

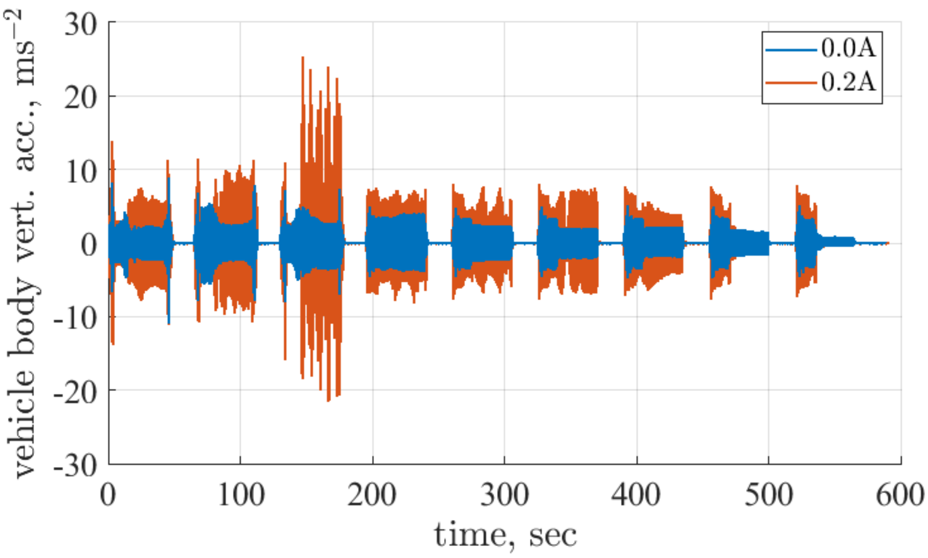

Fig. 8.11. Comparison of time diagrams of vertical acceleration for the front left vehicle body for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.11. Porównanie przebiegów czasowych pionowego przyspieszenia przedniej lewej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

Preliminary selection was performed for measurement data obtained during previous studies[41] similarly as it is shown in the above-presented figures. As a result, root-mean--squared values of front vehicle body vertical acceleration were evaluated in vibration steady state for consecutive frequencies of excitation generated by mechanical exciters. The transmissibility frequency characteristics evaluated for MR damper control currents equal to 0 and 0.07 ampere are presented in Figure 8.12. Compared to transmisssiblity characteristics presented in Figure 8.8. which were generated for a full-car model, a similar phenomenon can be noticed here where, for increasing suspension damping, the resonance frequency of the vehicle body is shifted to higher frequencies.

The full-car model was tuned ito map the dynamics of the actual experimental vehicle subjected to excitation generated by mechanical exciters. However, some discrepancies can be observed related to the resonance frequency exhibited for low suspension damping, which could be explained by weaker excitation of vehicle vibrations for such lower frequencies generated by mechanical exciters. Moreover, lower resonance frequency exhibited for higher suspension damping compared to simulation results can be caused by finite stiffness of rubber holders of shock absorbers, which were not taken into account in simulations. Also, lack of experimental results is visible for a frequency range of 8 to 9.5 Hz, which was intentionally excluded from experiments due to occurrence of resonance of mechanical exciters, which could damage them.

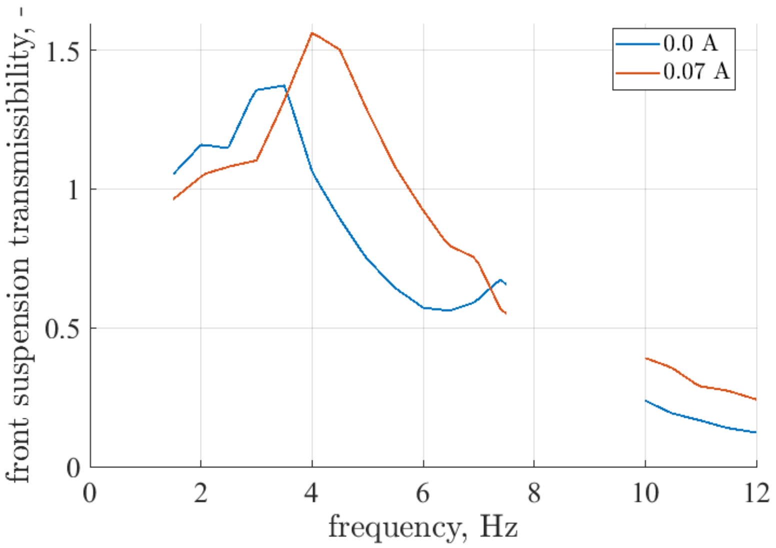

Fig. 8.12. Comparison of transmissibility characteristics of front vehicle body part evaluated for different electric currents supplying MR dampers in the vehicle based on results obtained during experiments carried out using laboratory setup for suspension diagnostics (Krauze et al., 2018)

Rys. 8.12. Porównanie charakterystyk współczynnika przenoszenia drgań przedniej części nadwozia wyznaczonych dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na stanowisku do diagnostyki zawieszenia[41] (Krauze et al., 2018)

Source: Own elaboration.

The application of the force sensor and suspension deflection sensors allowed the evaluation of the force-velocity characteristics for the front left suspension MR damper. Such characteristics presented in Figures 8.13 and 8.14 describe the operation of the MR damper during experiments carried out using the diagnostic station. They were evaluated separately for control currents equal to 0 and 0.2 ampere for excitation frequencies equal to 5 Hz (Figure 8.13) and 10 Hz (Figure 8.14). It is also visible that the characteristics presented in the following cover only a part of the piston velocity amplitudes compared to those reached during experiments carried out using the MTS experimental setup (Figure 8.4) which is caused by the limited amplitude generated by mechanical exciters and vehicle dynamics. Moreover, MR damper characteristics obtained using diagnostic station have a more oval shape, which can be caused by the fact that the force sensor additionally measures stiffness of shock absorber spring and finite stiffness of its rubber holders.

[41] Krauze P., Kasprzyk J., Kozyra A., Rzepecki J.: Experimental analysis of vibration control algorithms applied for an off-road vehicle with magnetorheological dampers, Journal of Low Frequency Noise, Vibration and Active Control, 2018, Vol. 37, No. 3, pp. 619–639.

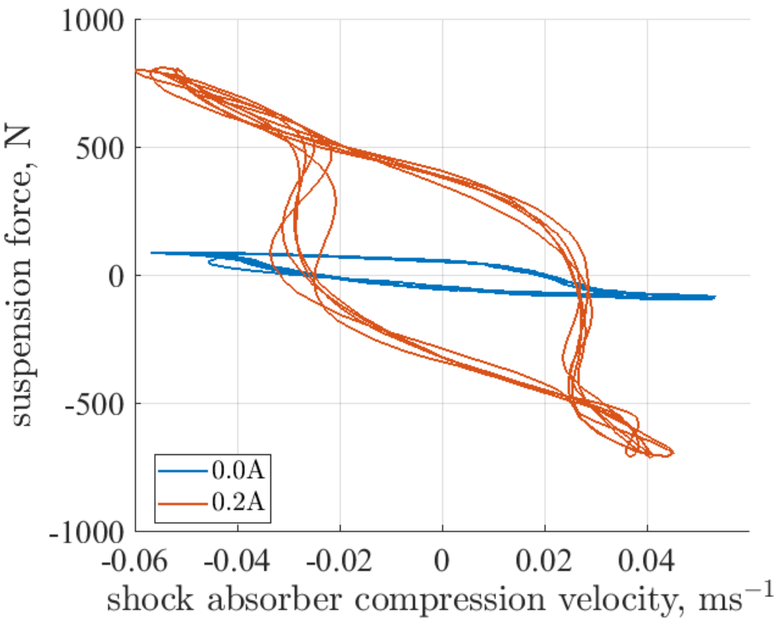

Fig. 8.13. Comparison of force-velocity characteristics evaluated for different electric currents supplying MR dampers in the vehicle obtained during experiments carried out using laboratory setup for suspension diagnostics for excitation frequency equal to 5 Hz

Rys. 8.13. Porównanie charakterystyk siła-prędkość wyznaczonej dla różnych prądów zasilających tłumik MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia dla częstotliwości wymuszenia równej 5 Hz

Source: Own elaboration.

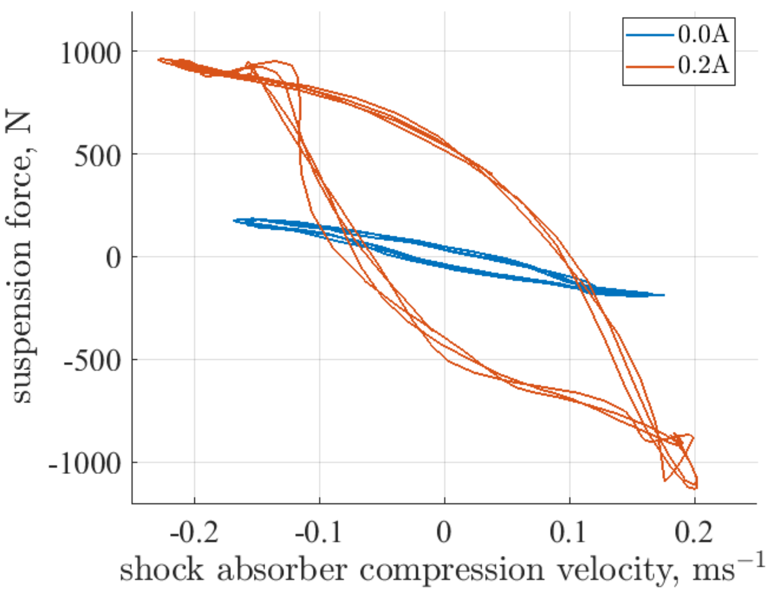

Fig. 8.14. Comparison of force-velocity characteristics evaluated for different electric currents supplying MR dampers in the vehicle obtained during experiments carried out using laboratory setup for suspension diagnostics for excitation frequency equal to 10 Hz

Rys. 8.14. Porównanie charakterystyk siła-prędkość wyznaczonej dla różnych prądów zasilających tłumik MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia dla częstotliwości wymuszenia równej 10 Hz

Source: Own elaboration.

8.3.2. Tests in terrain

The operation of suspension MR dampers during vehicle tests performed in terrain was analyzed based on two experiments carried out for MR damper control currents equal to 0 and 1 ampere. Analysis is carried out for the measurement signals of force and vehicle body vertical acceleration presented in the time diagrams in Figures 8.15 and 8.16. It can be noticed in Figure 8.15 that a higher control current causes an increase in damper force, further resulting in an increase in the acceleration amplitude of the vehicle body (Figure 8.16). Time diagrams of damper force was intentionally presented with offset, which allows one to show static load of vehicle wheel approximately equal to 1500 N.

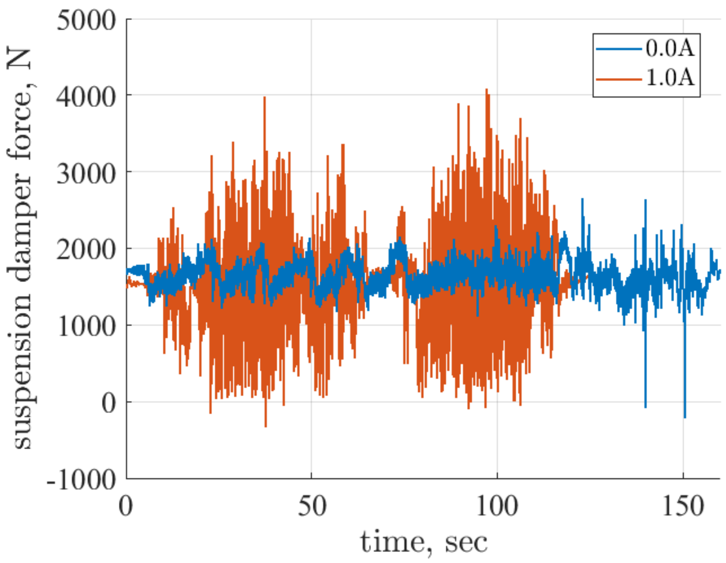

Fig. 8.15. Comparison of time diagrams of force generated in the front left suspension column for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out on a test route in terrain

Rys. 8.15. Porównanie przebiegów czasowych siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na drodze testowej w terenie

Source: Own elaboration.

The force and acceleration measurement data was also used for analysis of suspension operation in the frequency domain in Figures 8.17 and 8.18. It can be noticed that for greater control currents the power spectral density of damper force is increased for a wide frequency range. Furthermore, in this case a resonance peak is slightly noticeable close to frequency equal to 5 Hz which corresponds to the resonance peak previously analyzed for vehicle suspension with increased damping parameter in the case of simulation-based studies and experiments performed in diagnostic station. A similar resonance peak can be observed in Figure 8.18 for greater control currents that influence the power spectral density of the vertical acceleration of the vehicle body.

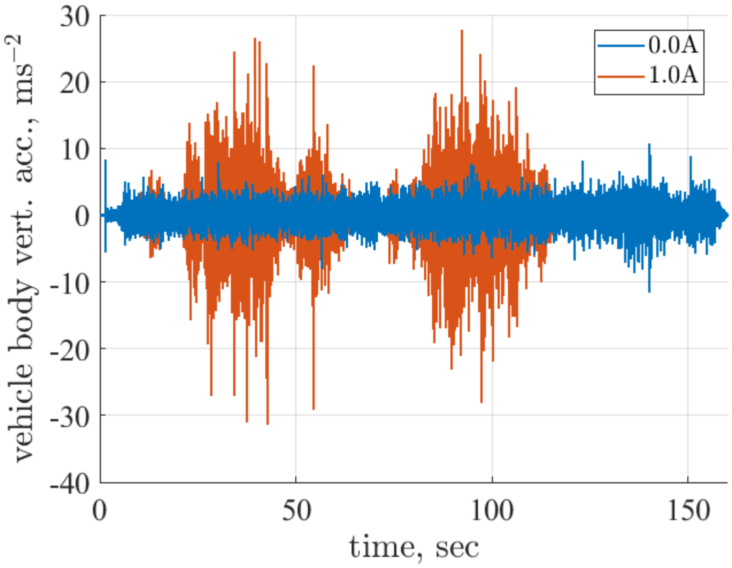

Fig. 8.16. Comparison of time diagrams of vertical acceleration for the front right vehicle body for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out on a test route in terrain

Rys. 8.16. Porównanie przebiegów czasowych pionowego przyspieszenia przedniej prawej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na drodze testowej w terenie

Source: Own elaboration.

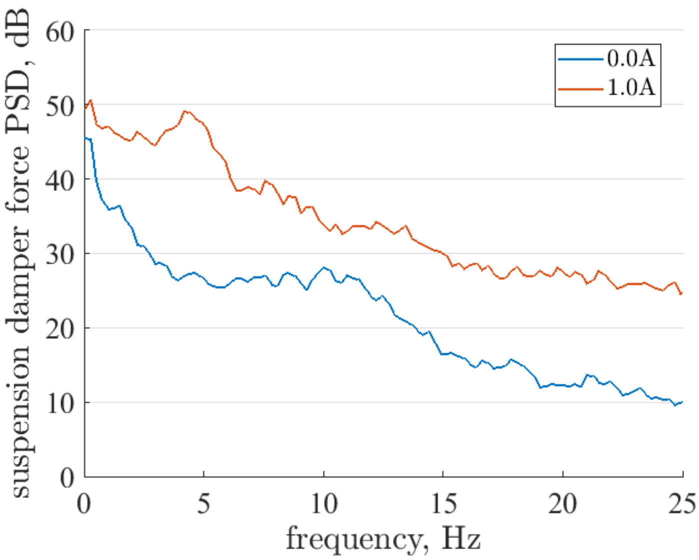

Fig. 8.17. Comparison of the power spectral density characteristics evaluated for the force generated in the left front suspension column for different electric currents supplying the MR dampers in the vehicle based on the results obtained during experiments carried out on a test route in terrain

Rys. 8.17. Porównanie charakterystyk gęstości widmowej mocy wyznaczonych dla siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na drodze testowej w terenie

Source: Own elaboration.

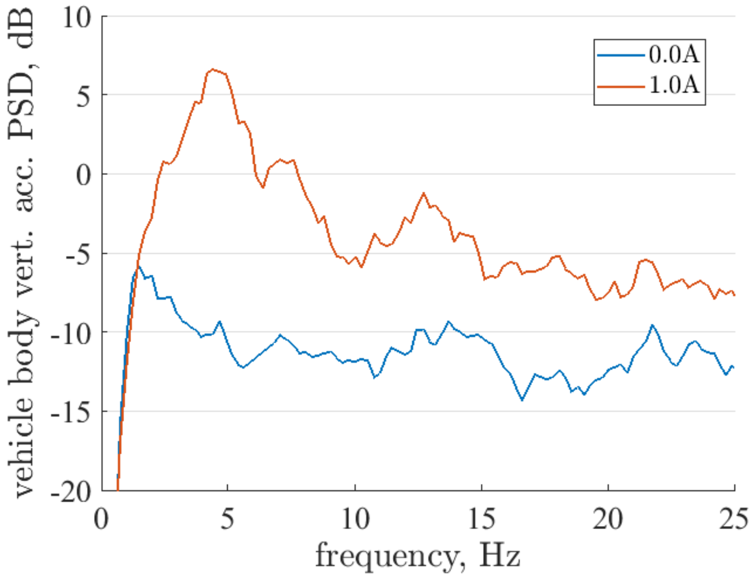

Fig. 8.18. Comparison of the power spectral density characteristics evaluated for the vertical acceleration of the front right vehicle body for different electric currents supplying MR dampers in the vehicle based on results obtained during experiments carried out on a test route in terrain

Rys. 8.18. Porównanie charakterystyk gęstości widmowej mocy wyznaczonych dla pionowego przyspieszenia przedniej prawej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na drodze testowej w terenie

Source: Own elaboration.

8.4. Conclusions

The presented study demonstrates potential methods of suspension control and diagnostics that are important with respect to the needs of future mobility. Adaptive suspension is crucial not only in urban areas, but also in the case of roads of lower quality, where information on road maps is limited. The main goal of electronically controlled suspensions is improvement of driving safety and ride comfort. Such key factors are always valid when moving on the ground along a given trajectory. Today, electrically supplied adaptive suspension can be further supported and integrated with electric vehicles as mobile energy resources.

However, in order to maintain the quality of the adaptive suspension during vehicle exploitation, the methods of suspension diagnostics for stationary and moving vehicles are crucial. The possibility of quick detection of suspension damages based on measurement data or additionally by comparing with the reference vehicle model has a decisive influence on the above-mentioned driving safety and ride comfort. The manuscript is especially dedicated to off-road vehicles where driving safety is of particular importance due to the higher center of gravity of such vehicles. Such vehicles also commonly show a lower degree of driver protection and move in much more difficult road conditions compared to road vehicles.

The experimental off-road vehicle in which the original shock absorbers were replaced by suspension MR dampers is a key element of the presented analysis. Measurement signals obtained from numerous sensors installed in the vehicle are used in the main suspension controller for the evaluation of the control currents that supply the MR dampers. As a result, such semi-active suspension allows for smooth modification of its damping parameter, which is its key advantage. It allows us to emulate not only various configurations which are specific to different types of vehicles, but also a certain degree of wear or damage to the suspension. Available accelerometers, force, and suspension deflection sensors allow for comprehensive analysis of vehicle response to such suspension configurations.

The presented manuscript begins with the state-of-the-art related to driving safety and ride comfort as well as related to methods of vehicle suspension modelling, control, and diagnostics. Further part reports components of the experimental vehicle including its construction, measurement, and control system and available suspension MR dampers. Next, approaches to validation of control algorithms are presented such as simulation-based research, dedicated experimental setup for suspension diagnostics, and a test route for experimental runs in terrain. It was shown based on experiments carried out using diagnostic station that the change of suspension damping parameter can be detected based on vehicle body acceleration, suspension deflection, or force generated by the suspension column. The effect of increased suspension damping was additionally analyzed based on transmissibility frequency characteristics that indicate the effect of coupling the wheel and vehicle body masses, as well as the effect of shifting the resonance frequency. Finally, the influence of suspension damping on vehicle response was investigated during tests carried out in terrain. Future research studies can focus on the development of an online identification of suspension parameters that will allow faster automatic detection of suspension wear or damage.

DOI:10.34918/87429

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9. NEW TECHNIQUES FOR THE PRODUCTION OF MATERIALS AND STRUCTURAL ELEMENTS IN THE CONSTRUCTION OF MODERN MEANS OF TRANSPORT

9.1. Introduction

In the development of any new technology, it is important to determine the moment at which the results of research carried out at laboratory and technological sites can provide a sufficient basis for developing assumptions and formulating unambiguous guidelines for launching a new technology under industrial conditions. It is therefore justified to determine the level of technological readiness, which will clearly and transparently determine the level of technological advancement, thus causing the interest of potential recipients.

The construction of modern means of transport depends on the possibility of using new materials and processing technologies. The new challenges facing the development of the mobility of the future are already well defined. It is mainly the use of light metal alloys and body steels of the new generation[3]. The primary purpose of using these materials is to reduce the weight of vehicles and aircraft, and thus energy consumption and increase range. Aluminum and magnesium alloys have long been the basic materials in the construction of aircraft structures. These are both casting alloys and alloys for plastic processing. We observe a growing trend of using these metal alloys also in the construction of vehicles. The development of electromobility has prompted car manufacturers to take measures to increase the share of these materials in the total

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[3] Sameer Kumar D., Tara Sasanka C., Ravindra K., Suman K.N.S.: Magnesium and its alloys in automotive applications – a review. American Journal of Materials Science and Technology, Vol. 4, No. 1, 2015, p. 12–30; Kuziak R., Kawalla R., Waengler S.: Advanced high strength steels for automotive industry. Archives of Civil and Mechanical Engineering, Vol. 8, No. 2, 2008, p. 103–117.

weight of the vehicle. In the construction of electric vehicles, we observe an increase in the use of materials with good electrical conductivity, primarily copper alloys. Copper alloys with an ultra-fine-grained and nanometric structure are an opportunity to obtain high strength and service life while maintaining good electrical conductivity.

In the aerospace industry, materials are used to work in high temperatures and aggressive corrosive environments of exhaust gases. Components made of these materials are subjected to significant, complex loads under cyclically variable temperature conditions. Extremely difficult operating conditions are also found in many vehicle power units. In turbochargers, high turbine rotational speeds are obtained in a corrosive environment of hot exhaust gases.

It is not sufficient to use titanium alloys in the construction of vehicles, in which high strength properties, resistance to various corrosive environments and high temperatures combined with low weight would constitute a competitive construction material. Already in the near future we will face the challenge of applying new technologies and advanced materials in the development of hydrogen technology and the widespread use of hydrogen in vehicle drives.

The use of new manufacturing techniques and advanced materials in the construction of means of transport requires in many cases a different, unconventional approach to the construction of technological equipment, the shape and kinetics of tool movement and the way of affecting the material during the manufacturing process. The aim of the chapter is to presents new technological possibilities of manufacturing materials and products, the use of which in the construction of modern means of transport, mobility of the future, may be an interesting alternative to conventional manufacturing techniques. The described devices are original construction studies, having no analogues in the commonly known constructions of machines and devices for plastic processing. Assessment of the current state of knowledge regarding the development of new methods of plastic processing intended for the processing of advanced materials and the production of products with complex geometry in one operation allows us to conclude that these methods significantly expand the range of possibilities of influencing the structure and properties of products. An important factor that determines the application possibilities of new methods of plastic formation is a significant level of technological readiness of TRL (Technology Readiness Level) methods.

9.2. Segmental shaping of ribbed and shell forgings of integral elements

The segmental shaping process is a plastic processing technology aimed at application in the automotive industry for the production of axisymmetric forgings with recesses, ribbed forgings such as shield, disc, ring and in the aerospace industry for the production of coatings and integral elements, which constitute an important group of products used in the construction of aircraft and helicopter plating. The production of products with such a complex geometry and shape is always a serious challenge for designers and technologists. Conventional technological processes of plastic processing, pressing and forging require significant shaping pressures and non-standard sizes of press working spaces. Too low shaping pressures are insufficient to effectively fill the die of the ribbed forging die, and integral elements due to their large surface area are produced in the processes of cavity machining from solid charge.

The essence of the new method of plastic shaping is the possibility of obtaining recesses of large area and depth as a result of summing the recesses of individual segments with a very small pressure area and a small single recess. This process allows the production of elements with a small thickness in relation to the transverse dimension of the forging and the execution of arbitrarily spaced, local recesses (ribs).

9.2.1. The concept of the segmentation process

The concept of the segmental shaping process provides for the transition from the designed solution to the shaping of ribbed axosymmetric forgings (a), through the shaping of longitudinal shell integral elements in the reciprocating movement of work rollers (b) and in the solution, in which the working rollers acting on the shaping segments perform a sliding, circumferential, one-way movement (c) (Fig. 9.1).

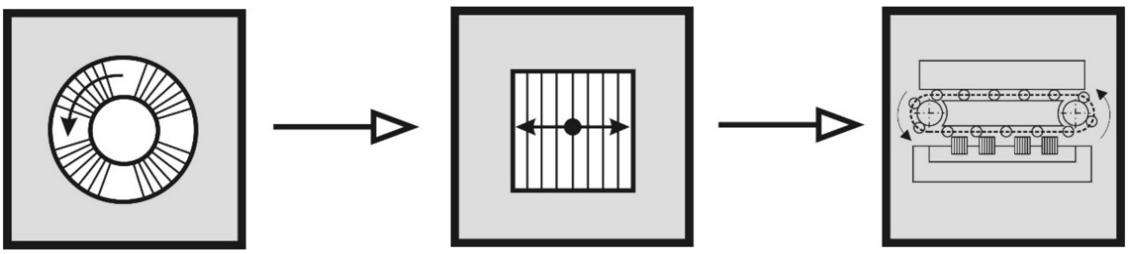


Fig. 9.1. A concept evolution of segmental forming of integral components and coverings
Rys. 9.1. Ewolucja koncepcji procesu kształtowania segmentowego elementów i pokryć integralnych
Source: Pawlicki J.: Niekonwencjonalne metody kształtowania plastycznego metali. Wydawnictwo Politechniki Śląskiej, Monografia nr 875, Gliwice 2021.

9.2.2. Segmenting of ribbed axiso-asymmetric forgings

The peculiarity of the instrument work is the design of the upper punch, which consists of a series of segments associated with each other. The working movement of the punch segments that causes deformation of the material is carried out by the interaction of the rollers embedded in the sockets on the upper retaining part of the segments. Depending on the number of rolls, the deformation can be carried out simultaneously by the same number of segments. For example, the use of three rollers causes the simultaneous working movement of three segments. The other segments are not currently participating in the deformation. The number of punch segments is a multiple of the number of rolls, for example: for a system of 3 rollers, 6, 9, 12 segments are provided. The segmented construction of the punch and the kinematics of the tool movement cause a local zone plasticization of the material. Plasticized zones appear in the material sequentially in a number equal to the number of rollers used and with a frequency that depends on the rotational speed of the cast in which the rollers are embedded. The kinematic diagram of the instrument is shown in Figure 9.2.

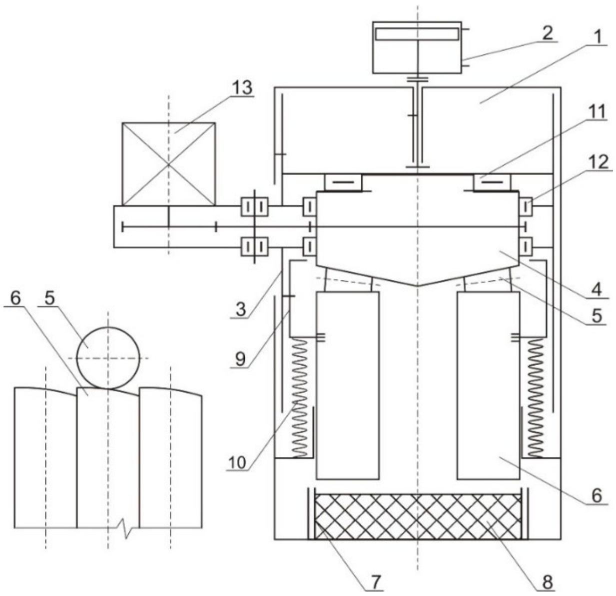


Fig. 9.2. Kinematic diagram of the compression device under the conditions of sequential local plastic deformation. 1. Body, 2. Hydraulic cylinder, 3. Slider, 4. Pressure plate, 5. Pressure roller, 6. Segmental punch, 7. Die, 8. Workpiece, 9. Guide ring, 10. Return spring, 11. Thrust bearing, 12. Radial bearing, 13. Drive

Rys. 9.2. Schemat kinematyczny przyrządu do ściskania w warunkach sekwencyjnego, lokalnego uplastycznienia. 1. Korpus, 2. Cylinder hydrauliczny prasy, 3. Suwak, 4. Talerz dociskowy, 5. Element toczny dociskowy, 6. Stempel segmentowy, 7. Matryca, 8. Materiał odkształcany, 9. Pierścień prowadzący, 10. Sprężyna powrotna, 11. Łożysko oporowe, 12. Łożysko poprzeczne, 13. Napęd

Source: Grosman F., Kurzydłowski J.K., Pawlicki J., Tomecki L.: Sposób kształtowania odkuwek i przyrząd do kształtowania odkuwek matrycą segmentową. Patent nr PL 210904 B1, 2012.

This way of realizing the deformation provides a significant reduction in the force necessary to shape. The total pressure of the press is accumulated on part of the surface of the deformed material, thus we obtain locally high values of unit pressures and the possibility of plasticizing materials characterized by significant plastic resistance. Thus, it allows you to effectively shape forgings in the form of rings, rings, ribbed wheels characterized by a large frontal surface and unfavorable from the point of view of shaping pressures small ratio of the height of the forging to the outer diameter. The high pressures found in traditional ways of shaping this type of forgings cause overloading of devices and the phenomenon of destruction of working tools, punches and dies. The tests were carried out on a simplified version of the instrument on a properly adapted press with a fluctuating matrix of the PXW-200 type. The hydraulic drive system of the PXW-200 was modified by introducing the main actuator speed control system. Figure 9.3 shows the individual elements of the prototype station in a six-anvil system[4]. The shaping tests of selected metal alloys were carried out on a model axis-asymmetric forging with recesses. Examples of forgings obtained in cold and hot forging tests of a model forging made of aluminum and titanium alloys are shown in Figure 9.4.

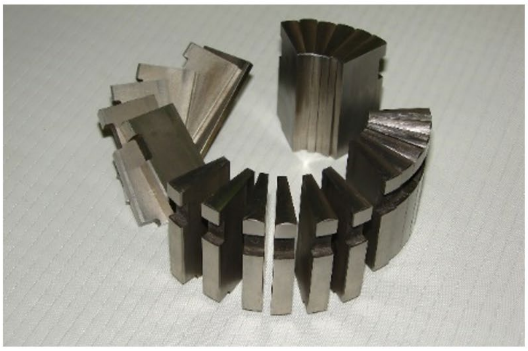
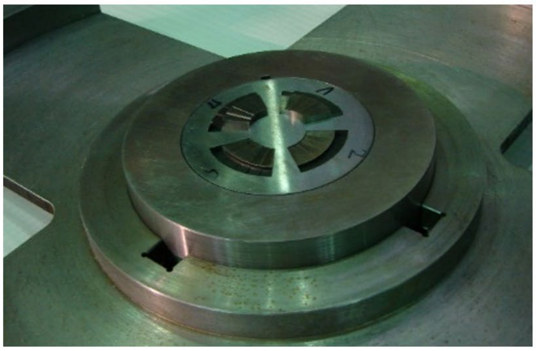
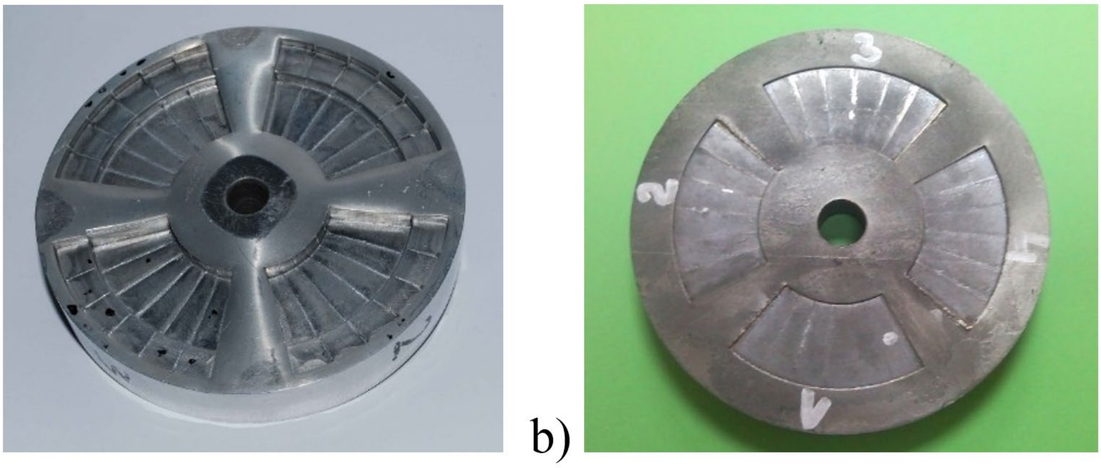
a)  b) 

Fig. 9.3. Working segments in a system of 6 anvils (a) and segment head mount with segments (b)
Rys. 9.3. Segmenty robocze w układzie sześciu kowadełek (a) i głowica segmentowa z zamontowanymi segmentami (b)
Source: Grosman F., Pawlicki J., Ziółkiewicz S.: Kształtowanie segmentowe odkuwek ze stopów tytanu i aluminium. Hutnik. Wiadomości Hutnicze, t. 77, nr 8, 2010, s. 388–391.

[4] Grosman F., Pawlicki J., Ziółkiewicz S.: Kształtowanie segmentowe odkuwek ze stopów tytanu i aluminium. Hutnik. Wiadomości Hutnicze, t. 77, nr 8, 2010, s. 388-391.



a) b)

Fig. 9.4. Forging made of PA38 aluminum alloy cold formed (a) and forging made of WT3-1 titanium alloy formed at temperature of 900°C (b)
Rys. 9.4. Odkuwka ze stopu aluminium PA38 kształtowana na zimno (a) i odkuwka ze stopu tytanu WT3-1 kształtowana w temperaturze 900°C (b)
Source: Grosman F., Pawlicki J., Ziółkiewicz S.: Kształtowanie segmentowe odkuwek ze stopów tytanu i aluminium. Hutnik. Wiadomości Hutnicze, t. 77, nr 8, 2010, s. 388–391.

9.2.3. Segmentation of shell integral elements

Segmental shaping of longitudinal integral elements is carried out in the reciprocating movement of work rollers. The total surface of the shaped element is divided into sequential areas, locally plasticized during the process by tool segments. A diagram of the segmental shaping device for longitudinal integrals is shown in Figure 9.5[5]. The peculiarity of the construction of the instrument is the design of the upper punch, which consists of a series of segments associated with each other. The working movement of the punch segments causing the deformation of the material is carried out by pressing the rollers on the upper thrust part of the segments. The segmented construction of the punch and the kinematics of the tool movement cause local, zone plasticization of the material. Plasticized zones appear in the material sequentially in a number equal to the number of rollers used and with a frequency that depends on the speed of sliding movement of the rollers.

[5] Grosman F., Pawlicki J., Tomecki L., Kurzydłowski J.K.: Przyrząd do obróbki plastycznej matrycą segmentową. Patent nr PL 211137 B1, 2012.

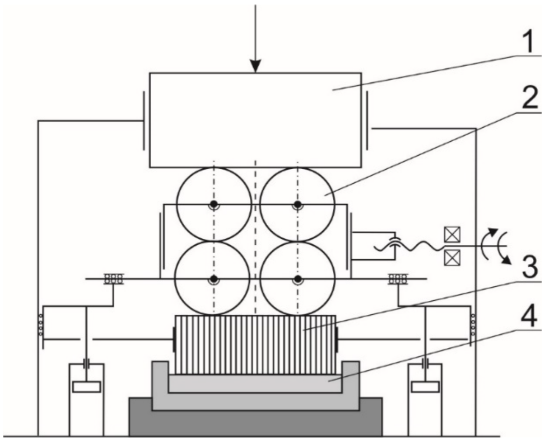


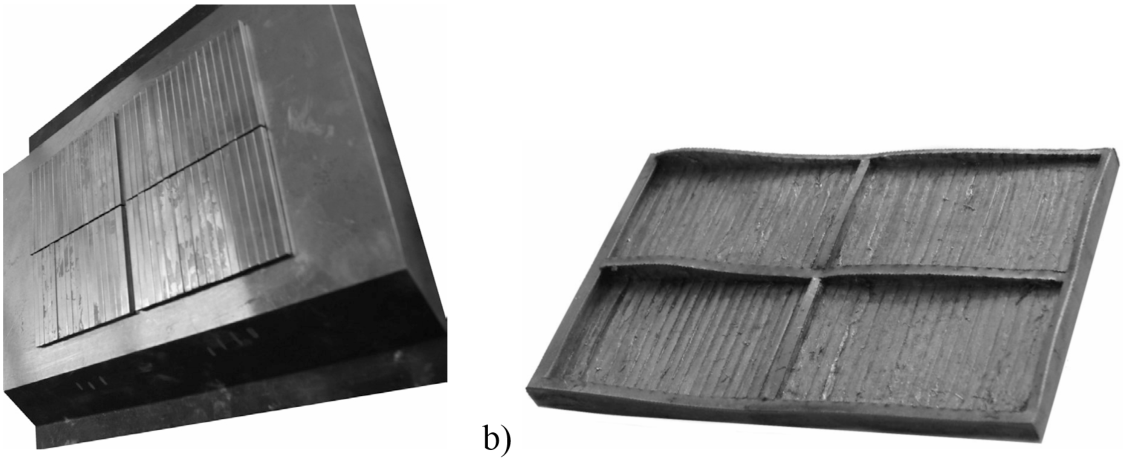
Fig. 9.5. A segmental forming device with reciprocating movement of the working rolls: 1. Press ram, 2. Rolls, 3. Segmental punch, 4. Workpiece

Rys. 9.5. Przyrząd do kształtowania segmentowego z posuwisto-zwrotnym ruchem rolek roboczych: 1. Suwak prasy, 2. Rolki, 3. Stempel segmentowy, 4. Materiał odkształcany

Source: Grosman F., Pawlicki J., Tomecki L., Kurzydłowski J.K.: Przyrząd do obróbki plastycznej matrycą segmentową. Patent nr PL 211137 B1, 2012.

The reciprocating movement of the rollers is carried out by means of an additional drive. The device allows for a stepless adjustment of the rollers the speed of displacement and the pressure force of the press. This way of realizing the deformation provides a significant reduction in the force necessary to shape. The total pressure of the press accumulates on part of the surface of the deformed material, thus obtaining locally high values of unit pressures and the possibility of plasticizing materials characterized by significant plasticizing stress.

Attempts to shape the segmented model integral element with recesses for aluminum alloy. The input material was an aluminum sheet with dimensions of 215 x 135 x 12 mm. A four-section stamp was used. There are 20 segments in each section. You can change the number of segments in a section as you wish. Segmental shaping tools and a ready--made model integral with recesses are shown in Figure 9.6.



a) b)

Fig. 9.6. Segments grouped in sectors within the punch frame (a) and the ribbed model element of aluminum alloy. Dimensions: 215 x 135 x 20 mm (b)
Rys. 9.6. Segmenty zgrupowane w sektorach wewnątrz oprawy stempla (a) i modelowy element użebrowany ze stopu aluminium. Wymiary: 215 x 135 x 20 mm (b)
Source: Grosman F., Pawlicki J., Ziółkiewicz S.: Kształtowanie segmentowe odkuwek ze stopów tytanu i aluminium. Hutnik. Wiadomości Hutnicze, t. 77, nr 8, 2010, s. 388-391.

On the surface of the recesses there are clear traces of the impact of individual segments. The height of the edges of the section of the element, ribs, is uneven and regularly corrugated, which is due to the diverse conditions of flow of plastic material. This phenomenon is defined by the principle of the least resistance to flow. Each point of the deformed body moves in the direction in which it encounters the least resistance. In technological practice, it is important to know the trajectory along which the resistance of plastic flow will be the smallest. When compressing with friction occurring in the contact zone of the frontal surface of the punch with the deformed material, the trajectory of the displacement of the points of the body is determined according to the principle of the shortest normal to the cross-section circumference.

The concept of the evolution of the development of segmental shaping technology also presents a solution in which working rollers affecting the shaping segments perform a sliding, peripheral, one-way movement (Fig. 9.1). This method of segmental shaping is designed for the manufacture of long elements with a repetitive, periodic structure of recesses along the length. The shaped element is moved during deformation on the press table relative to the position of the shaping mechanism. In this way, subsequent zones along the length of the element are deformed. The mechanism of movement of rollers due to their unidirectional movement is less technically complicated. However, this design solution requires a complementary technical analysis and assessment of implementation costs.

9.3. Volumetric shalping of forgings with oscillating torsion

The design of the device is an original technical solution covered by patent protection[6]. The technological device has been designed in such a way that the axial force is realized indirectly by a testing machine or a hydraulic press. The versatility of changing the location of the device and the possibility of using hydraulic systems of the strength of the testing machine or hydraulic press greatly simplify the construction of the device and reduce the cost of execution. The kinematic diagram of the device is shown in Figure 9.7.

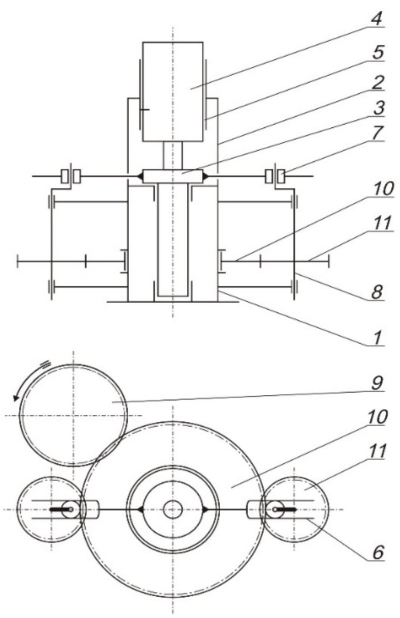


Fig. 9.7. Kinematic diagram of a compression device with oscillating torsion. 1. Lower body, 2. Upper body, 3. Lower punch, 4. Upper punch, 5. Non-rotating slidable bearing, 6. Fork − lower punch arm, 7. Roller, 8. Crankshaft (eccentric), 9. Driving gear, 10. Ring gear, 11. Gear wheel

Rys. 9.7. Schemat kinematyczny przyrządu do ściskania z oscylacyjnym skręcaniem. 1. Korpus dolny, 2. Korpus górny, 3. Stempel dolny, 4. Stempel górny, 5. Łożysko przesuwne nieobrotowe, 6. Widełki − ramię dolnego stempla, 7. Rolka, 8. Wał wykorbiony (mimośrodowy), 9. Koło zębate napędzające, 10. Pierścień zębaty, 11. Koło zębate

Source: Grosman F., Kurzydłowski J.K., Pawlicki J., Tomecki L.: Przyrząd do obróbki plastycznej metali. Patent nr PL 211139 B1, 2012.

[6] Grosman F., Kurzydłowski J.K., Pawlicki J., Tomecki L.: Przyrząd do obróbki plastycznej metali. Patent nr PL 211139 B1, 2012.

The device has the following possibilities of deformation tests of metallic materials and pressing of powders[7]:

- conventional compression in various friction conditions, e.g. frictionless compression, in dry friction conditions,
- conventional compression in a closed matrix with the possibility of adjustable radial metal flow,
- oscillating torsion (no postaxial movement of the upper punch),
- compression with simultaneous oscillating twisting under conditions of free radial flow of metal,
- compression with simultaneous oscillating twisting under high quasi-hydrostatic pressures,
- powder pressing by means of a pressing attachment mounted on the lower movable stamp.

The implementation of these shaping attempts is possible due to the additional kinematic function of the device, related to the oscillatory movement of the lower punch, which significantly increases the intensity of the given plastic deformations. The original kinematics of the device gives great possibilities of physical modeling of the structure of metals, implementation of tests of material sensitivity to changing the deformation path and practical application to conduct a technological swelling operation. The device in the process of work rests on the traverse of the testing machine. It has a smooth adjustment of the compression speed, torsion frequency and torsion angle amplitude. Kinematic quantity settings allow you to change the torsion angle in the range from 0° to ±8°. The frequency of fluctuations of the lower ft punch is regulated by an inverter in the range from 0 to 1.8 Hz with the possibility of increasing the maximum frequency to 2.6 Hz.

9.3.1. Mechanical and structural effects of the process

The results of studies carried out on a representative group of metallic materials showed that both a decrease in the compression velocity v_c, while maintaining a constant

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[7] Pawlicki J., Grosman F.: Charakterystyki materiałowe dla oscylacyjnego skręcania. Prace Naukowe Politechniki Warszawskiej, z. Mechanika, nr 201, 2003, s. 139–144; Pawlicki J., Grosman F.: Analysis of power□energy effects for processes with forced deformation path. Archives of Civil and Mechanical Engineering, Vol. 4, No. 3, 2004, p. 45–55.

twist frequency f_t, and an increase in the frequency of twisting f_t, at a constant compression velocity v_c cause a decrease in the level of average unit pressures[8]. It can be concluded from this that the course of the force characteristics in the compression process with oscillating twisting is mainly determined by the ratio of the torsion angle to the increase in the crease Δh. The ratio of component deformation, caused by twisting to component deformation, caused by compression, is a parameter characterizing the path of deformation (d_ε), which determines the structural and force effects of deformation. Changing the process parameters, thus the proportion of the component deformations, results in the rotation of the main axes of the stress state and a change in the value of the main stresses. The stress state scheme also changes along the radius of the cylindrical sample and in the axis of the sample for $r = 0$, corresponds to the uniaxial state of stress $\sigma_1 > 0$, and the remaining principal stresses $\sigma_2 = \sigma_3 = 0$. When considering the force parameters in the axis of the sample F, > 0 and $M_t = 0$.

Figure 9.8 shows the course of the mean unit loads obtained during compression, under conditions of change of the strain path during the test. The additional oscillating movement of the lower punch causes a marked decrease in the amount of pressure in any phase of the compression process. The mean unit pressure remains constant with increasing crease and for the corresponding value of the actual crumb $\varepsilon = 1.1$ (logarithmic deformation) is almost 100 MPa less. Stopping during the oscillating twist test produces the opposite effect, an immediate increase in pressures that reach the level of conventional compression pressures.

[8] Rodak K., Pawlicki J.: Effect of compression with oscillatory torsion processing on structure and properties of Cu. Journal of Materials Science and Technology, Vol. 27, 2011, p. 1083–1088; Rodak K., Pawlicki J.: Microstructure characterization of Cu processed by compression with oscillatory torsion. Materials Characterization, Vol. 94, 2014, p. 37–45; Rodak K., Pawlicki J.: Efficiency of the compression with oscillatory torsion method in grain refinement in Al. Archives of Civil and Mechanical Engineering. Vol. 16, 2016, p. 805–812.

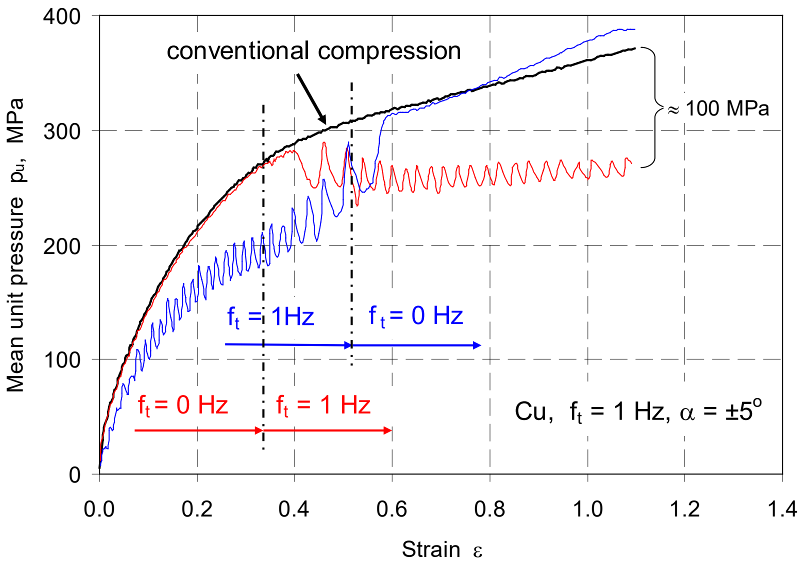

Fig. 9.8. The effect of strain path on mean unit pressure values for cylindrical copper samples subjected to compression with oscillatory torsion

Rys. 9.8. Wpływ drogi odkształcenia na wartość średnich nacisków jednostkowych w próbie ściskania z oscylacyjnym skręcaniem próbek walcowych z miedzi

The compression process with oscillating twisting causes certain structural effects in the material. Their nature and intensity of occurrence depend on the set kinematic parameters of the process and the amount of cumulative deformation (total replacement deformation). Figure 9.9 shows the effect of fragmentation of the material structure (Cu) resulting from a change in process parameters and, consequently, an increase in total replacement deformation[9]. The high intensity of deformation and the dynamics of the process cause that this process is heat-activated in microareas. In order to obtain unambiguous results for such a complex deformation process, an area representative of microstructural studies was selected from the center of the height of the cylindrical sample at a distance of approx. 0.8 of the sample radius.

[9] Rodak K., Pawlicki J.: Microstructure characterization of Cu processed by compression with oscillatory torsion. Materials Characterization, Vol. 94, 2014, p. 37–45.

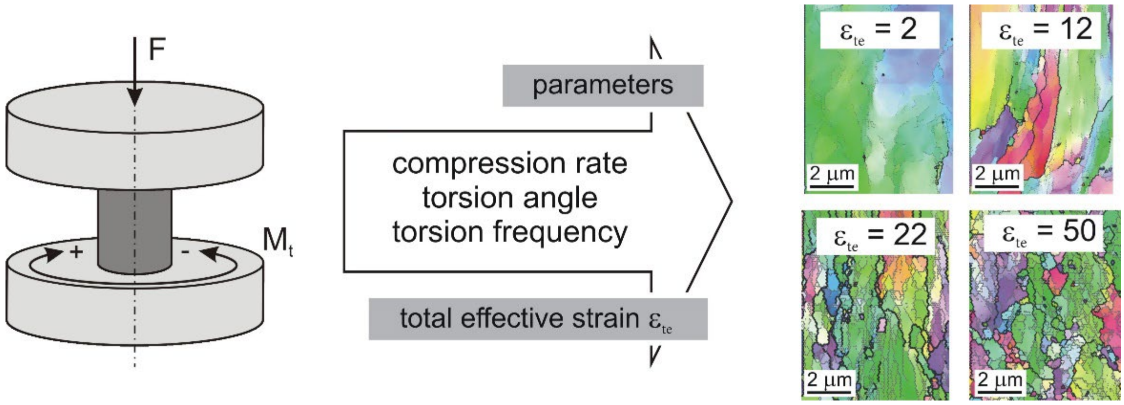

Fig. 9.9. Influence of process parameters on the total equivalent deformation ε_{te} and the grain grinding effect

Rys. 9.9. Wpływ parametrów procesu na całkowite odkształcenie zastępcze ε_{te} i efekt rozdrobnienia ziarna

Source: Rodak K., Pawlicki J.: Microstructure characterization of Cu processed by compression with oscillatory torsion. Materials Characterization, Vol. 94, 2014, p. 37–45.

An interesting phenomenon accompanying the compression process with oscillating twisting is the shape of the samples after deformation. Figure 9.10 shows the view of copper samples after compression with oscillating twisting and conventional compression under dry friction conditions[10]. Shape of compressed samples with oscillating torsion it is similar to the geometry of cylindrical samples compressed in frictionless conditions. The lack of pronounced sphericity of the surface forming the cylindrical sample (barrel-likeness) indicates that the resulting deformations in the volumes of compressed samples are uniform. A similar effect of the lack of sphericity of the surface forming cylindrical samples was also found for a significant group of test materials (Al, steel grade 0H18N9, titanium alloy Grade 1)[11].

[10] Rodak K., Pawlicki J.: Effect of compression with oscillatory torsion processing on structure and properties of Cu. Journal of Materials Science and Technology, Vol. 27, 2011, p. 1083–1088.

[11] Rodak K., Pawlicki J.: Microstructure of ultrafine□grained Al produced by severe plastic deformation. Arch. Mater. Sci. Eng., Vol. 28, No. 7, 2007, p. 409–412.

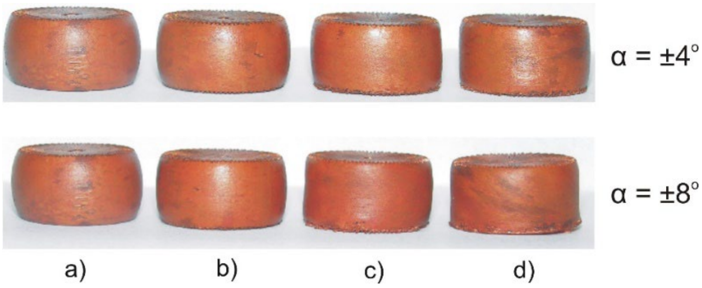

Fig. 9.10. A view of samples subjected to oscillatory torsion with strain rate of $v_t = 0.6$ mm/s for torsion angles $\alpha = \pm 4°$ and $\alpha = \pm 8°$: a) a sample compressed without torsion, b) $f_t = 0.4$ Hz, c) $f_t = 1$ Hz, d) $f_t = 1.8$ Hz

Rys. 9.10. Widok próbek po ściskaniu z oscylacyjnym skręcaniem z prędkością ściskania $v_t = 0{,}6$ mm/s dla kątów skręcania $\alpha = \pm 4°$ i $\alpha = \pm 8°$: a) próbka ściskana bez skręcania, b) $f_f = 0{,}4$ Hz, c) $f_f = 1$ Hz, d) $f_f = 1{,}8$ Hz

Source: Rodak K., Pawlicki J.: Effect of compression with oscillatory torsion processing on structure and properties of Cu. Journal of Materials Science and Technology, Vol. 27, 2011, p. 1083–1088.

9.3.2. Model die forging process

The conducted compression tests with oscillating twisting supported the activities aimed at developing a model forging process of matrix forgings of osivosymmetric forgings with a reversibly torsional lower matrix. In industrial conditions, this process corresponds to the process of die forging in an open matrix (with an outflow). Figure 9.11 shows the process diagram and spatial visualization of the tools. The basic assumption that determines the effectiveness of this method of deformation is the selection of the forging shape, which will allow the transfer of a variable cyclically twisting torque at the height of the charge. The input material for forging should have at both ends an appropriate cross-section (square, triangular, etc.), associated with the parts of the blank in the lower and upper matrix. Another way is to conduct the initial forging phase without reversible movement of the lower matrix until the selected lower part of the blank (e.g. with a square cross-section) is filled, which will allow the transfer of cyclically variable twisting torque to the material in the further phase of the forging process, but already with the reversible movement of the die running. In the deformation process, to initiate the beneficial effects of additional deformation of the form from twisting, it is necessary to perform at least one full twisting cycle.

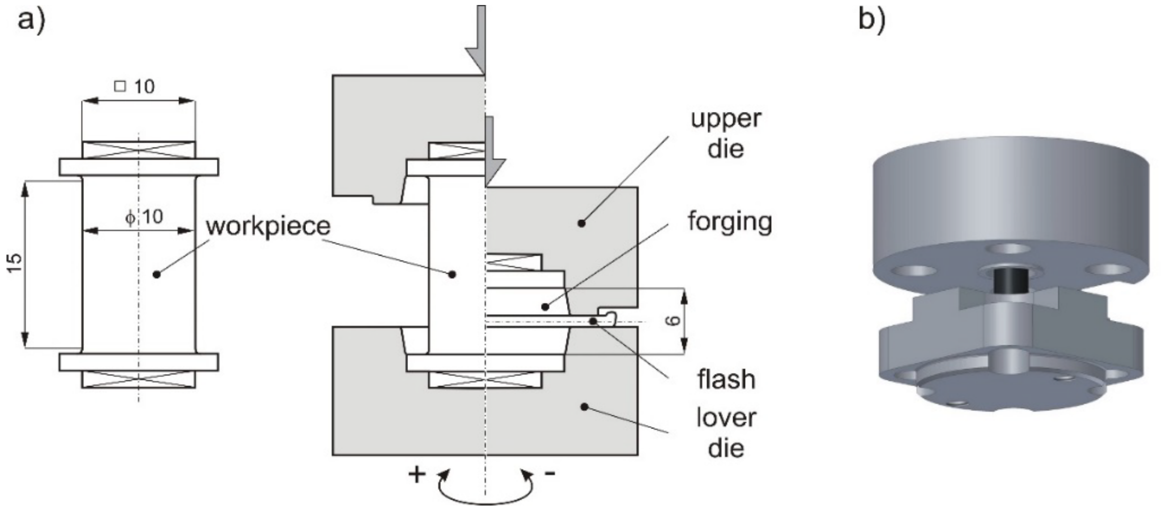

Fig. 9.11. Scheme of the compression process with a reverse torsion bottom die (a) and spatial visualization of tools (b)
Rys. 9.11. Schemat procesu ściskania z rewersyjnie skrętną dolną matrycą (a) i wizualizacja przestrzenna narzędzi (b)

The most effective solution, as well as the one that can cause the effect of uniform deformation in the volume of the forging, is the simultaneous torsional movement of both dies, upper and lower. However, such a solution further complicates the design of the device. In a conventional die forging process, one of the dies is stationary, so it is easier to develop and install an additional mechanism to actuate torsional movements in the lower die.

One of the possibilities of using the new shaping method is forging the heads of bolts and screws, special fasteners for the mining industry and the construction of railway infrastructure.

9.3.3. Plastic shaping of metals supported by additional shear stresses

The concept of plastic shaping supported by additional shear stresses is a derivative of work and research carried out on a compression device with oscillating twisting. The compression process with oscillating twisting can be used for cylindrical samples, in industrial applications of axesymmetric forgings such as disc, ring, disc, etc. The high efficiency of the process as well as the ability to control the structure of the material to obtain the desired strength and functional properties were the basis for the development of the assumptions of the concept of the station for the production of forgings with an elongated shape based on the same method of loading. As a result, two concepts for the drive of the reciprocating movement of the lower matrix, based on the eccentric mechanism and hydraulic cylinders, were developed. Both studies are the subject of a patent[12].

Figure 9.12 shows a modification of the instrument consisting in the use of two hydraulic cylinders (5, 6) to drive the lower punch (3) and setting in an oscillating reciprocating motion. This structural solution for instrument construction is less mechanically complicated and easier to perform. The design of the instrument is also more compact, which can be important when placing the instrument on the table of the hydraulic press.

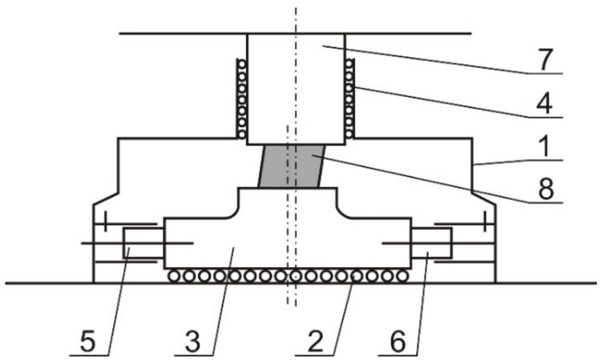

Fig. 9.12. Scheme of the compression device aided by additional shear stresses: 1. Body, 2. Float guide, 3. Lower punch, 4. Float guide, 5. Left hydraulic cylinder, 6. Right hydraulic cylinder, 7. Upper punch, 8. Workpiece

Rys. 9.12. Schemat przyrządu do ściskania wspomaganego dodatkowymi naprężeniami ścinającymi: 1. Korpus, 2. Prowadnica toczna, 3. Stempel dolny, 4. Prowadnica toczna, 5. Cylinder hydrauliczny lewy, 6. Cylinder hydrauliczny prawy, 7. Stempel górny, 8. Materiał odkształcany

Source: Grosman F., Kurzydłowski J.K., Pawlicki J., Tomecki L.: Sposób plastycznego kształtowania wyrobów metalowych i przyrząd do plastycznego kształtowania wyrobów metalowych. Patent nr PL 211138 B1, 2012.

This method of shaping the plastic material consists in simultaneous compression and oscillating form deformation in the direction perpendicular to the direction of pressure of the punches. As a result of such a movement of tools, the material compressed between the punch and the die is subjected to cyclic loading with a transverse force causing the occurrence of additional shear stresses in the deformed material, which improves the conditions for filling the die blanks, resulting in the effect of "closing" and "bonding" material discontinuities and changing the structure and

[12] Grosman F., Kurzydłowski J.K., Pawlicki J., Tomecki L.: Sposób plastycznego kształtowania wyrobów metalowych i przyrząd do plastycznego kształtowania wyrobów metalowych. Patent nr PL 211138 B1, 2012.

properties of the material. The end result of such a process is to reduce the number of deficiencies in the production of products and semi-finished products resulting from the local effects of loss of material consistency.

Plastic shaping supported by additional shear stresses, allows to obtain a number of new effects in terms of geometric features and the quality of manufactured products. The main advantage of this method of manufacture is the possibility of obtaining products with a lower relative height (ratio of height to transverse dimension) and a homogeneous and fine-grained structure. This method can be used mainly for the production of machine components with very high static, dynamic and fatigue strength. It is particularly suitable for the manufacture of high-power motor components, pumps and gearboxes, and components for medicine (homogeneous material structure and high strength).

9.4. Rolling process with the cyclical, axial movement of rollers

Rolling with Cyclic Movement of Rolls (RCMR) can be an interesting and competitive alternative to the well-known methods of large plastic deformation SPD (Severe Plastic Deformation). A big advantage of the process is the possibility of quick application in industrial conditions for the production of ultra-bottom-grained materials and nanocrystalline. The device was made on the basis of an unconventional technical solution of the movement of shaping tools and equipped with a complete measuring system recording all parameters of the process course.

The RCMR rolling station is designed in a duo roller system. The mechanism of post-axial movement of rollers is the original design solution of the experimental rolling mill[13]. The rolling process carried out in this way is characterized by the possibility of obtaining much higher effective deformation values. The RCMR process differs from conventional rolling by the additional transverse movement of the rollers. The band is deformed by simultaneously reducing the height and forced movement of the layers of material in a direction perpendicular to the main direction of rolling. In the conventional rolling process, the height of the band is reduced (crease) and the flow of material in the direction perpendicular to the direction of rolling (widening) is insignificant. Figure 9.13 shows the kinematic diagram of the device in the RCMR process.

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[13] Grosman F., Pawlicki J., Korbel A., Bochniak W., Kiełpiński R., Tomecki L.: Sposób walcowania, zwłaszcza metali oraz klatka walcownicza do walcowania, zwłaszcza metali. Patent nr 203220 B1, 2009.

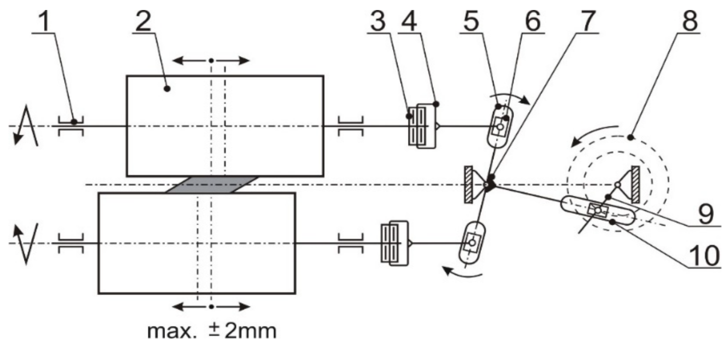


Fig. 9.13. Scheme of the setup of RCMR. 1. Bearing, 2. Working roll, 3. Thrust bearing, 4. Hushing, 5. Yoke, 6. Stone sliding, 7. Swivel, 8. Eccentric bush, 9. Eccentric shaft, 10. Stone sliding

Rys. 9.13. Schemat kinematyczny urządzenia RCMR. 1. Łożysko, 2. Walec, 3. Łożysko wzdłużne, 4. Obudowa, 5. Jarzmo, 6. Kamień ślizgowy, 7. Czop, 8. Tuleja mimośrodowa, 9. Wał mimośrodowy, 10. Kamień ślizgowy

Source: Grosman F., Pawlicki J., Korbel A., Bochniak W., Kiełpiński R., Tomecki L.: Sposób walcowania, zwłaszcza metali oraz klatka walcownicza do walcowania, zwłaszcza metali. Patent nr 203220 B1, 2009.

The implementation of the axial movement of the rollers is forced by a pendulum built on pins 7 yoke 5, which alternately affects the working rollers 2 moving them along their axis. Yoke 5 is set in motion through an eccentric system consisting of an eccentric shaft 9 and an eccentric sleeve 8, which cyclically move yoke 5. This cyclic movement of yoke 5 is transmitted to the housings of 4 bearings 3 and through the two-way thrust bearing 3 on the working rollers 2. The magnitude of the postaxial movement of working rollers 2 is regulated by changing the position of the eccentric sleeve 8 on the eccentric shaft 9. The eccentric sleeve 8 is adjustable relative to the eccentric shaft 9 as a result, so the resultant eccentricity can vary from zero to the sum of partial eccentricities. This allows for a smooth adjustment of the deflection of the yoke of 5, and thus a smooth and stepless axial movement of the working rollers 2.

The design of the device allows quick replacement of rollers, setting the gap between the rollers and the desired size of the axial stroke of the rollers. Adjustments and settings of the device allow to change the deflection of the cylinder from the central position to ±2 mm and the frequency of transverse fluctuations of the rollers up to 3 Hz. The transverse deformation of the band is forced by parallel grooves made on the surfaces of the roller barrels. The device is equipped with a measuring system from BMCM − Germany. The measurement system is controlled, processed and stored using NEXT VIEW 3.4. program.

9.4.1. Mechanical and structural effects of the process

In the RCMR rolling process, it is possible to perform large total plastic deformations. The amount of deformation accumulated in the material (rolled band) depends on the number of culverts and can be adjusted. The process also has no limits on the geometric sizes of the input material, which distinguishes the RCMR method from other methods of large plastic deformations. It is practically possible to continuously deform a band of any length, which gives the method a practical and industrial character.

Figure 9.14 shows the effect of the number of culverts (single deformations) on the total deformation value in the conventional rolling process and RCMR[14].

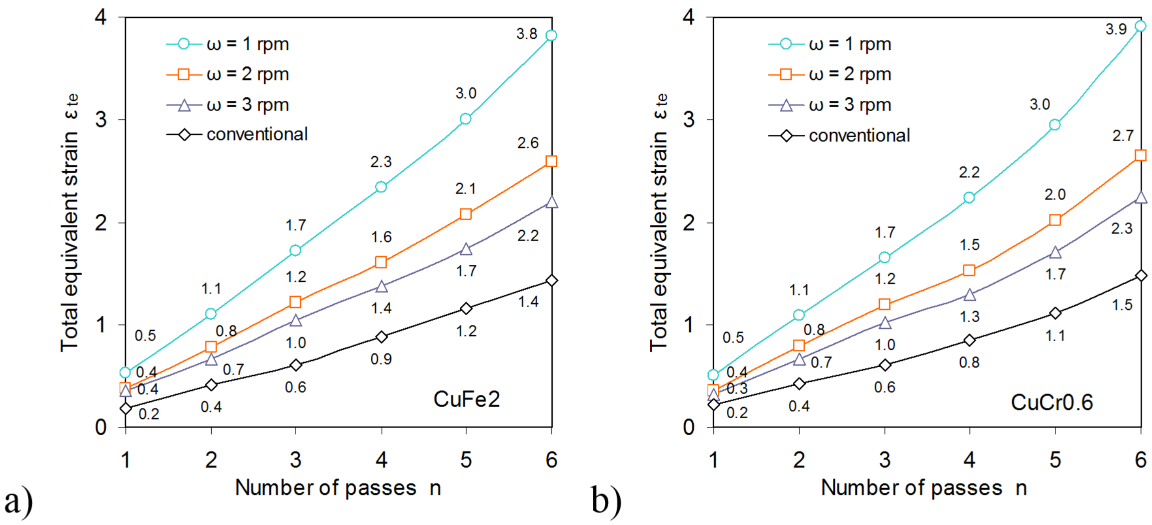


Fig. 9.14. Influence of rolling speed on the value of total equivalent strain depending on the number of passes n, with a constant displacement amplitude transverse rollers A and frequency f: a) CuFe2 alloy, b) CuCr0.6 alloy

Rys. 9.14. Wpływ prędkości walcowania na wartość całkowitego odkształcenia zastępczego w zależności od liczby przepustów n, przy stałej amplitudzie przemieszczenia poprzecznego walców A i częstotliwości f: a) stop CuFe2, b) stop CuCr0,6

Source: Płachta A., Pawlicki J.: Wpływ procesu walcowania z poosiowym, cyklicznym ruchem walców na strefy lokalnych odkształceń w stopie CuFe2. Rudy i Metale Nieżelazne, R. 60, nr 11, 2015, s. 559–563.

The resulting value of total deformation after 6 culverts in the RCMR process is about 2.5 times higher than that obtained in the conventional rolling process. This result was obtained for the rotational speed of the rollers ω = 1 rpm. The total replacement

[14] Płachta A., Pawlicki J.: Wpływ procesu walcowania z poosiowym, cyklicznym ruchem walców na strefy lokalnych odkształceń w stopie CuFe2. Rudy i Metale Nieżelazne, R. 60, nr 11, 2015, s. 559–563.

strain values for speeds ω = 2 rpm and ω = 3 rpm are correspondingly lower. This regularity is due to a decrease in the number of postaxial movements of the rollers along the length of the rolling basin with an increase in the rotational speed of the rollers (rolling speed). The value of the total replacement deformation in the RCMR process is defined as the mean value of the deformation over the length of the rolling basin.

Observations of the structure of cross-sections of bands in subsequent culverts in the RCMR process, they indicate a significant impact of the additional transverse movement of the rollers on the evolution of local deformation zones. Figure 9.15 shows microstructural images of the cross-sections of the samples for selected culverts.

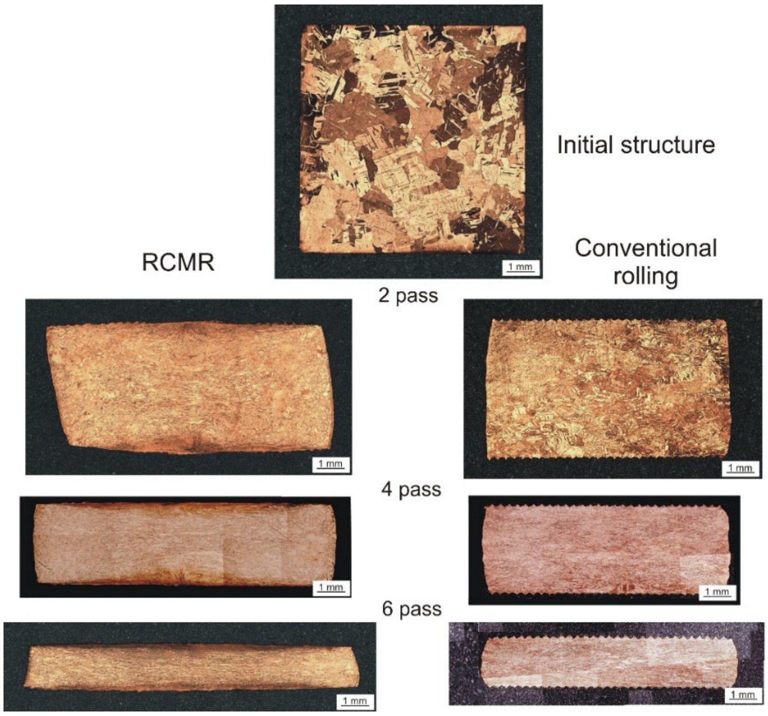


Fig. 9.15. Microstructural images of sample cross sections in selected passes in the RCMR and conventional rolling process

Rys. 9.15. Obrazy mikrostrukturalne przekrojów poprzecznych próbek w wybranych przepustach w procesie RCMR i w procesie walcowania konwencjonalnego

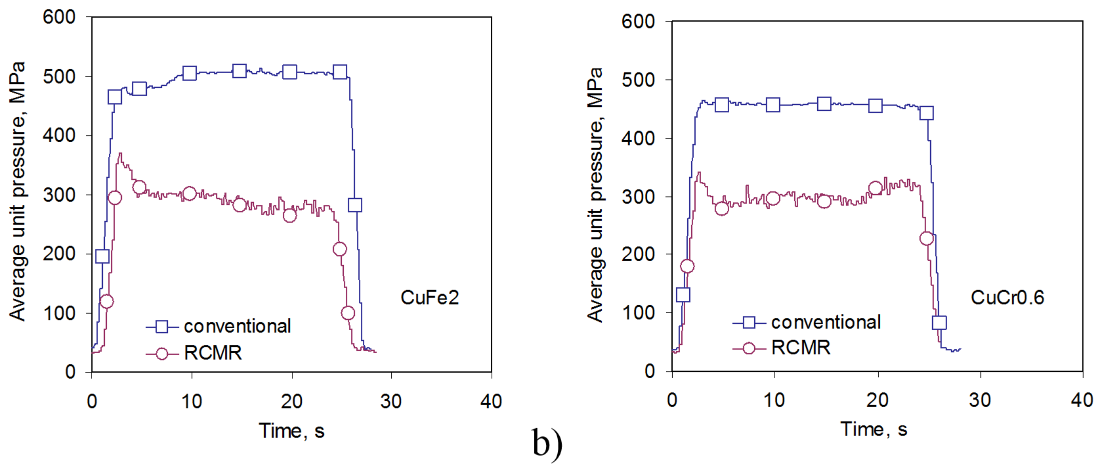
The transverse, cyclic movement of the rollers already causes in the initial phase of deformation (in the initial culverts) the formation of zones strongly deformed at the contact surfaces with the upper and lower rollers. Near-surface intensively deformed zones migrate in subsequent culverts from the surface towards the center of the band and cover an increasing volume of the band. The effectiveness of the influence of rollers on the size and location of large plastic deformations increases with the number of culverts.

Studies of hardness distributions (HV0.2) on cross-sections of samples showed the convergence of results with zones of local intense deformations. In the RCMR process, high hardness values occur in zones near contact with the upper and lower rollers. In the process of conventional rolling, the hardness distribution is more even over the cross-section of the band. Areas with a high hardness value occur throughout the entire cross-section of the sample. In the sample formed in the RCMR process, the hardness values are lower in the zones of intensive plastic deformation, although the total replacement deformation is much greater than that obtained in the conventional rolling process.

The deformation softening effect observed in the RCMR rolling process is caused by a permanent change in the load scheme. This phenomenon has already been observed in laboratory studies and technological processes, where the change in the orientation of the main stresses is revealed by a decrease in the hardness of the materials in the area of the center of the deformation basin. The phenomenal analysis of the specific mechanism of plastic deformation of metals under the influence of external conditions, as a result of cyclical forcing and a change in the path of deformation, was carried out by A. Korbel[15].

The effect of softening of the deformation is also visible on the unit pressure waveforms of the rolling. Figure 9.16 shows examples of the characteristics of the average unit loads of rolling in the RCMR and conventional rolling processes. The level of pressure in the RCMR process in subsequent culverts is significantly lower compared to conventional rolling. The phenomenon of a decrease in rolling pressure is independent of the type of material, which has been confirmed by laboratory studies carried out on a large number of metals. The power and energy analysis of this issue is the subject of further experimental research supported by the assessment of thermal effects using a thermal imaging technique.

[15] Korbel A.: Structural and mechanical aspects of localized deformation in Al-Mg alloy. Arch. Metall. 32, 1987, p. 377–392; Korbel A., Martin P.: Microstructural events of macroscopic strain localization in prestrained tensile specimens. Acta Metall. 36, 1988, p. 2575–2586.



a) b)

Fig. 9.16. Characteristics of average unit pressures of rolling in the 5th pass for CuFe2 (a) and CuCr0.6 (b)
Rys. 9.16. Charakterystyki średnich nacisków jednostkowych walcowania w 5 przepuście dla CuFe2 (a) i CuCr0,6 (b)

9.5. Summary

The positions presented in the work are unique in the world of research and technological devices and can be the basis for the launch of a new technology in industrial conditions. The knowledge and practical application of the strength and structural effects of new shaping methods can significantly change the current perception of the directions of development of plastic processing technology.

The use of the presented technologies will allow more effective control of the microstructure and properties of products in the stages of their production and processing. This issue is particularly important in the situation of using new construction materials in the construction of means of transport, m.in new generation high-strength body steels and light metal alloys. In laboratory and technological tests, high efficiency of grain grinding methods has been demonstrated also on the nanometric scale. In the methods there are large reserves in terms of modifying the structure of metals and obtaining controlled mechanical properties.

Segmented shaping is primarily a higher material yield resulting from the replacement of material-intensive machining with machining. It also possible to produce monolithic integral coatings and front forgings with a favorable course of material fibers according to the shape of the element. It is also allows for the possibility of producing monolithic integral coatings and front forgings with high-strength ribbing and favorable fiber flow of the material in accordance with the shape of the element. In addition to increasing the level of strength properties, the method allows reducing the weight of the product, reducing the number of joints, thus places of stress concentration and sources of crack generation, which affects the durability and improvement of safety. In the technological process, it is possible to reduce the number of operations and quickly adapt the existing machine park, thus reducing investment outlays.

The compression method with oscillating torsion is particularly effective in the production of die forged products. The uniform distribution of deformations in the volume of the forging, significant cumulative deformations, and high strength indicate the possibility of using the method for the production of forgings such as a disc, disc, also used in the construction of vehicles as well as fasteners of railway infrastructure, heads of railway screws and screws for the mining industry.

The rolling process with cyclic, axial movement of rollers is a technology that can be used in large-scale and mass production, with high efficiency, which puts the process in a convenient implementation situation. The most important benefits of its use are, above all, obtaining a large total deformation, the desired and controlled structure of the material, and shortening the production cycle of rolling by reducing the number of component operations (the number of culverts). It is possible to produce sections with a gradient structure, also ultrafine-grained and nanometric and production of, for example, conductive copper alloy rails used in the construction of electromobile means of transport and elements of energy railway infrastructure. Due to the occurrence of large, cyclically variable shear stresses that effectively penetrate the band at height, the method can be used in the recycling processes of layered composite materials.

The presented unconventional plastic shaping have a not yet fully recognized, application potential. However, the level of advancement of research and technological tests is sufficient to take action to implement new methods of plastic processing in industrial conditions.

DOI:10.34918/87430

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10. MODERN WELDED CONSTRUCTIONS FOR A SMART CITY AND THE TRANSPORT OF THE FUTURE

10.1. Introduction

As a result of updating the regulations on exhaust emissions in road transport, numerous additional components are installed in motor vehicles, such as: exhaust gas catalysts, diesel particulate filters, additional exhaust system components, e.g. injectors. On the one hand, these components significantly reduce the emission of harmful substances, and on the other, they contribute to increasing the total weight of the vehicle. According to literature data, the weight of heavy goods vehicles with additional components installed, it can increase by even 200 kg[4].

To prevent this from happening, vehicle manufacturers and constructors are looking for solutions to reduce the weight of the vehicle, i.e. making the structure slimmer, while maintaining its appropriately high functional properties. Therefore, in recent years there has been a rapid development of materials used for the production of thin-walled vehicle structures. These structures are usually made using the following bonding methods[5]:

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[3] Silesian University of Technology, Faculty of Transport and Aviation Engineering, Department of Road Transport, e-mail: Boguslaw.Lazarz@polsl.pl.
[4] Skowrońska B., Szulc J., Chmielewski T., Golański D.: Wybrane właściwości złączy spawanych stali S700 MC wykonanych metodą hybrydową plazma + MAG. Welding Technology Review, 2017, Vol. 89, No 10, p. 104–111. http://dx.doi.org/10.26628/ps.v89i10.825; Skrzymowski W.: Podesty ruchome i przejezdne budowa i eksploatacja. Wydawnictwo i Handel Książkami „KaBe” s.c., Krosno 2011; Polko W.: Konserwacja podestów ruchomych przejezdnych, Wyd. Kabe, Krosno 2015.
[5] Skowrońska B., Szulc J., Chmielewski T., Golański D.: Wybrane właściwości złączy spawanych stali S700 MC wykonanych metodą hybrydową plazma + MAG. Welding Technology Review, 2017, Vol. 89, No. 10, p. 104–111. http://dx.doi.org/10.26628/ps.v89i10.825.

- MIG / MAG shielding gas welding,
- TIG welding,
- submerged arc welding,
- laser welding,
- MMA welding,
- electron beam welding,
- plasma and microplasma welding,
- spot and seam welding.

The mentioned processes are applicable to the construction of most means of road, air and sea transport[6]. Welding processes include: truck frames, skeletons of self-supporting bodies, passenger car bodies, self-unloading bodies, fixed bodies (tanks, containers), cabins, elements of mobile platforms, etc.[7].

Striving to reduce the total weight of vehicles and increase the safety of their use has translated into an increased interest of manufacturers in new grades of steel that can be used in the automotive industry. This trend concerns especially high-strength steels such as HSS (High-Strength Steel) and AHSS (Advanced High-Strength Steel). The use of high-strength steels in means of transport allows for a significant reduction in vehicle weight, which translates into a reduction in fuel consumption and the reduction of harmful gas emissions to the environment. These steels are being used more and more in the construction of means of transport due to their high[8]:

- temporary tensile strength,
- yield point,
- fatigue strength,
- impact strength.

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[6] Skrzymowski W.: Podesty ruchome i przejezdne budowa i eksploatacja. Wydawnictwo i Handel Książkami „KaBe" s.c., Krosno 2011; Polko W.: Konserwacja podestów ruchomych przejezdnych, Wyd. Kabe, Krosno, 2015.

[7] Silva A., Szczucka-Lasota B., Węgrzyn T., Jurek A.: MAG welding of S700MC steel used in transport means with the operation of low arc welding method. Welding Technology Review, 2019. Vol. 91, No 3, p. 23–30; Jaewson L., Kamran A., Jwo P.: Modeling of failure mode of laser welds in lap-shear speciments of HSLA steel sheets. Engineering Fracture Mechanics, 2011, Vol 1, p. 347–396.

[8] Darabi J., Ekula K.: Development of a chip-integrated micro cooling device. Microelectronics Journal, 2016, Vol. 34, Issue 11, p. 1067–1074, https://doi.org/10.1016/j.mejo.2003.09.010; Hadryś D.: Impact load of welds after micro-jet cooling. Archives of Metallurgy and Materials, 2015, Vol. 60, Issue 4, pp. 2525–2528, https://doi.org/10.1515/amm-2015-0409; Golański D., Chmielewski T., Skowrońska B., Rochalski D.: Advanced Applications of Microplasma Welding. Biuletyn Instytutu Spawalnictwa w Gliwicach, 2018, Vol. 62, Issue 5, p. 53–63. http://dx.doi.org/10.17729/ebis.2018.5/5; Krupicz B., Tarasiuk W., Barsukov V.G., Sviridenok A.I.: Experimental Evaluation of the Influence of Mechanical Properties of Contacting Materials on Gas Abrasive Wear of Steels in Sandblasting Systems. Journal of Friction and Wear,2020, Vol. 41, Issue: 1, pp. 1–5.

Implementation of high-strength steels into vehicle structures made it possible to reduce the thickness of metal sheets of vehicle load-bearing structures, with a simultaneous increase in mechanical properties in comparison with unalloyed steels[9]. Therefore, HSS and AHSS steels have found application as a new material used in the production of mobile platforms. The strength properties of these steels, especially their high immediate tensile strength at the level of 1400 MPa, made it possible to design a thin-walled pole-boom structure with significantly increased load capacity and operating range, compared to the structure used so far[10]. An example of a movable platform with the possibility of extending the mullion-boom is shown in Figure 10.1.

The advantages determining the rapid development of HSS and AHSS steels in the automotive industry are also their easy forming and machining.

Welding of high-strength steels is not well known yet, which translates into a limitation of their use in welded structures. Welded joints of high-strength steels are characterized by worse mechanical properties than the parent material, especially lower tensile strength and impact strength[11]. Moreover, the connectors are prone to breakage. This is due to the dominant martensitic structure in the parent material and the presence of coarse ferrite in the joint structure.

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[9] Shwachko V. l.: Cold cracking of structural steel weldments as reversible hydrogen embrittlement effect. International Journal of Hydrogen Energy, 2000, no. 25; Łabanowski J., Fydrych D.: Oznaczanie zawartości wodoru dyfundującego w stopiwie. Prace Naukowe Politechniki Warszawskiej, II Sympozjum Naukowe Zakładu Inżynierii Spajania Politechniki Warszawskiej, Warszawa 2008.

[10] Hadryś D.: Impact load of welds after micro-jet cooling. Archives of Metallurgy and Materials, 2015, Vol. 60, Issue 4, pp. 2525–2528, https://doi.org/10.1515/amm-2015-0409.

[11] Darabi J., Ekula K.: Development of a chip-integrated micro cooling device. Microelectronics Journal, 2016, Vol. 34, Issue 11, p. 1067–1074, https://doi.org/10.1016/j.mejo.2003.09.010; Hadryś D.: Impact load of welds after micro-jet cooling. Archives of Metallurgy and Materials, 2015, Vol. 60, Issue 4, pp. 2525–2528, https://doi.org/10.1515/amm-2015-0409.

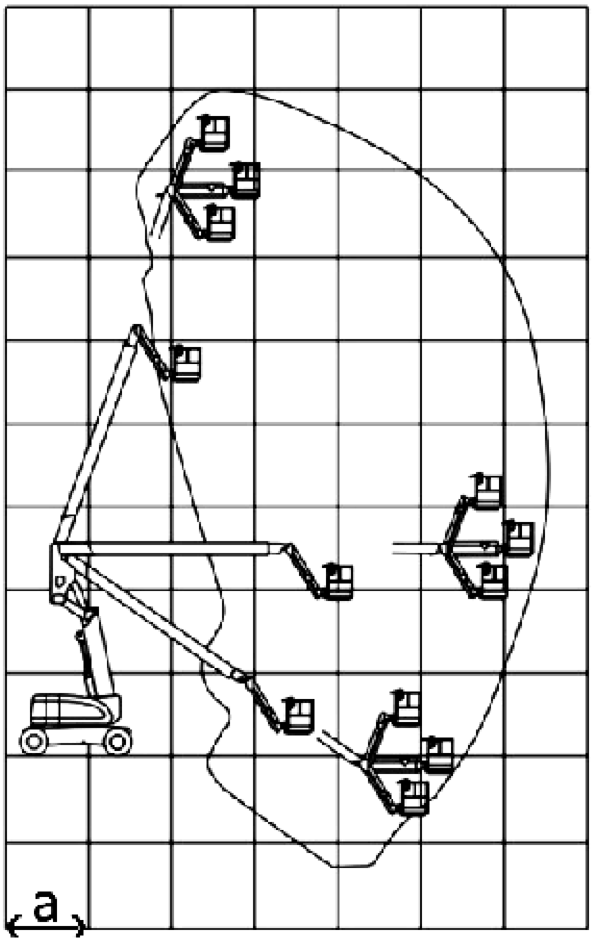

Fig. 10.1. Working area for the cantilever mobile platform, where a = 1 m
Rys. 10.1. Obszar roboczy dla podestu ruchomego przejezdnego wysięgnikowego, gdzie a = 1 m
Source: Based on https://www.jlg.com/pl-pl/equipment/engine-powered-boom-lifts/telescopic/400-series/400s-2015.

The aim of the study is to select welding parameters for selected steel grades from the HSS and AHSS groups intended for use in the construction of modern means of transport. It was decided that the new proposed material and technological solution should meet the passive safety requirements of the obtained welded structure, the measure of which, in welded structures, is good impact strength and fatigue strength of joints.

10.2. Materials used for research

To assess the weldability, it was decided to select the following new grades of high--strength steels: S 960 QL (representative of the HSS material group) and DOCOL 1200M and DOCOL 1400M steels (steels from the AHSS group). The mechanical properties of the tested HSS and AHSS steels, as delivered, are shown in Table 10.1.

Table 10.1

Selected HSS i AHSS steels and their mechanical properties

Steel grade	YS, MPa	UTS, MPa	Elengation A_5,%
DOCOL 1400	1155	1380	7.3
DOCOL 1200	1007	1220	10.5
S 960 QL	975	1107	9.1

Source: Own study.

High tensile strength and correspondingly high plastic properties (Table 10.1) result from the chemical composition of the tested steel grades. The information contained in Table 10.2 shows that these steels contain a much higher content of titanium than classic unalloyed structural steels and a controlled, low sulphur content of 0.001–0.002% in the case of AHSS steel (Table 10.2). These elements, to a large extent, determine the mechanical properties of the discussed steel grades.

Table 10.2

Selected HSS i AHSS steels and their chemical composition

Stal	C, %	Si,%	Mn,%	P, %	S,%	Al,%	Nb,%	V, %	Ti,%
S960 QL	0.12	0.25	1.3	0.02	0.01	0.015	0.05	0.05	0.017
DOCOL 1200M	0.14	0.21	1.3	0.008	0.001	0.045	0.015	0.02	0.025
DOCOL 1400M	0.17	0.2	1.4	0.009	0.002	0.04	0.015	0.01	0.025

Source: Silva A., Szczucka-Lasota B., Węgrzyn T., Jurek A.: MAG welding of S700MC steel used in transport means with the operation of low arc welding method. Welding Technology Review, 2019. Vol. 91, No 3, p. 23–30.

Plates were prepared and welded for testing the weldability of HSS and AHSS steels 4 mm thick, with a V-bevel with an angle of 60 °. The joints were made using the MAG (Metal Active Gas) process with shielding gas in the form of the recommended mixture: 90% Ar + 10% CO_2. The UNION X96 electrode wire was selected for welding the steel. The chemical composition of the electrode wire is given in Table 10.3.

Table 10.3

Electrode wire UNION X96 – chemical composition

C, %	Si, %	Mn, %	P, %	Cr, %	Mo, %	Ni, %	Ti, %
0.11	0.8	1.8	0.01	0.45	0.65	2.45	0.007

Source: Own study.

The analysis of the information provided in Table 10.3 shows that the carbon content in the electrode wire is similar to the content of this element in the tested high-strength steels, while the content of other elements is at a different level. First of all, nickel, chromium and molybdenum are additionally introduced in the electrode wire to increase the strength and plastic properties of the weld metal. Welding for all tested materials was carried out with the use of a forming copper backing. The samples of all joined steels were prepared in two variants:

- without preheating,
- with a preheating of 105°C, of a drying nature, which mainly leads to a reduction in the hydrogen content in the weld
- without preheating,
- with a preheating of 105°C, of a drying nature, which mainly leads to a reduction in the hydrogen content in the weld.

The MAG welding parameters of the tested steels were as follows:

- the diameter of the UNION X96 electrode wire was 1.0 mm,
- arc voltage was 18.5 V,
- welding current 122 A,
- the dirrect current source (+) on the electrode,
- the welding speed for each material was changed twice: 330 mm/min and 430 mm/min.

The samples prepared in this way were sent for testing.

10.3. Research

After welding the samples with the MAG process with shielding gas in the form of the recommended mixture 90% Ar + 10% CO_2MAG non-destructive testing (NDT) was carried out, which included:

- visual examination (VT); according to the requirements of PN-EN ISO 17638, evaluation criteria according to EN ISO 5817,
- magnetic particle testing (MT; according to PN-EN ISO 17638, the test was assessed according to EN ISO 5817, with a device for testing with a magnetic flaw detector, type REM – 230.

The research was aimed at selecting joints without welding defects and incompatibilities. Only properly made joints were qualified for further analysis. The temporary tensile strength test of the welded elements of the mobile landing was carried out on the INSTRON 3369 testing machine, with three tests for each sample. Due to the fact that the minimum strength of 550 MPa corresponds to the required tensile strength of the materials used for the mobile landing elements, joints with strength equal to or higher than this level were submitted for further tests. A bend test was performed on these materials.

The parameters of the samples were as follows: sample width b = 20 mm, sample thickness 3 mm, pin d = 14 mm, support spacing d + 3a = 31 mm and the required bending angle of 180°. Five measurements were made in a bending test for each sample from the root side and from the face side. Samples that passed all tests with positive results and were characterized by the best parameters for use in the construction of mobile platforms, they were additionally tested:

- in terms of fatigue strength with the number of load cycles close to the expected value for the steel fatigue limit for 2 million cycles.
- and then subjected to an impact test. The impact test was performed at -20°C and 0°C.

10.4. Results and discussion

The results of non-destructive testing of joints, obtained in accordance with the methodology presented in the previous sections of the study, are presented in Table 10.4.

Table 10.4

NDT results

Sample	Steel	Pre-heating, 105°C	Welding speed, mm/min	observation
Pb1	S960 QL	no	330	cracks
Pb2	DOCOL 1200M	no	330	good weld
Pb3	DOCOL 1400M	no	330	cracks
Pz1	S960 QL	105°C	330	good weld
Pz2	DOCOL 1200M	105°C	330	good weld
Pz3	DOCOL 1400M	105°C	330	good weld
Pb4	S960 QL	no	430	cracks
Pb5	DOCOL 1200M	no	430	good weld
Pb6	DOCOL 1400M	no	430	cracks
Pz4	S960 QL	105°C	430	cracks
Pz5	DOCOL 1200M	105°C	430	good weld
Pz6	DOCOL 1400M	105°C	430	cracks

Source: Own study.

Based on the information in the table, it can be concluded that the choice of line energy and preheating have a significant impact on the properties of the joint. Dry pre--heating is recommended for correct welding of S960 QL and DOCOL 1400 steels. The value of linear energy has a similar effect on the quality of joints from the analyzed steel grades. Welding with too high a speed of 430 mm/min more often leads to cracks than welding at a lower speed of 330 mm/min. The analysis of the obtained test results showed that only in the case of DOCOL 1200M steel, there were no cracks during welding without preheating and with heating, and no significant influence of the welding speed on the quality of the obtained joints was noted.

After the joints were assessed by non-destructive testing, the temporary tensile strength of the welded elements of the mobile landing was tested. The following samples were tested on the INSTRON 3369 testing machine: Pb2, Pz1, Pz2, Pz3, Pb5, Pz5, the quality of which was satisfactory after the NDT tests (Table 13.4). The results of the endurance tests (average of 3 tests) are presented in Table 10.5.

Table 10.5

Tensile resistant results

Sample	Steel	UTS	A_5
Pz1	S960 QL	611	7.8
Pb2	DOCOL 1200M	711	8.3
Pz2	DOCOL 1200M	719	8.2
Pz5	DOCOL 1200M	703	8.2
Pb5	DOCOL 1200M	701	8.2
Pz3	DOCOL 1400M	903	6.6

Source: Own study.

The tabular data shows that only in the only case, for DOCOL 1400M steel, a very high tensile strength of over 900 MPa was obtained. After welding DOCOL 1200M steel, regardless of the parameters used (linear energy, preheating), the temporary tensile strength of over 700 MPa was always obtained. The strength of the joint made of 960 QL steel was over 600 MPa. By analysing the results, it can be concluded that the obtained values of the tensile strength of the joints are significantly lower than the tensile strength of the parent material (see Table 13.1). The results of the measurements show that all joints had acceptable strength for the construction materials intended for the analysed means of transport. All joints had a tensile strength well above the required 550 MPa. Moreover, it was found that all the tested samples had relatively good and comparable plastic properties.

Then, a bend test was carried out for all tested joints at the required bending angle of 180°. In the bending test, 5 measurements were made for each sample from the root side and from the face side. Regardless of the type of steel used, no cracks were found in the joints in the joints and in the HAZ, both on the root and face sides. No other non--conformities were found either. This means that the evaluation of the tests is positive for all tested materials.

The penultimate stage of the research was to check the fatigue strength. Joints made of S960 QL, DOCOL 1200 and DOCOL 1400 steel were tested and they were made with a welding speed of 330 mm/min and with the use of preheat at 105°C. These joints were selected because they had the best strength properties, as determined in previous tests, and were free from welding imperfections.

The fatigue test with a fixed value of stress applied at the level of 250 MPa for steel S960 QL (sample Pz1), showed the occurrence of cracking at the number of load cycles 1 913 257, close to the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that with a stress value slightly below 250 MPa, the material will have an infinite fatigue life. The fatigue limit of the tested welded joint of S960 QL steel was estimated at 225 MPa.

The fatigue test with the applied stress at the level of 450 MPa for the DOCOL 1200M steel (sample Pz2), showed the occurrence of cracking at the number of load cycles 1,893,201, as low as the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that at a stress value slightly below 450 MPa, the material will have infinite fatigue life. Therefore, the fatigue limit of the tested welded joint of DOCOL 1200M steel was estimated at 430 MPa. The fatigue test with the applied stress at the level of 500 MPa for the DOCOL 1400M steel (sample Pz3), showed the occurrence of cracking at the number of load cycles 1,845,378, close to the expected value for the steel fatigue limit for 2 million cycles. Based on this result, it can be concluded that with a stress value slightly below 500 MPa, the material will have infinite fatigue life. In this case, the fatigue limit of the tested welded joint of DOCOL 1400M steel was estimated at 480 MPa.

Positive results of the joint fatigue strength tests allow for a statement that the design of the means of transport will meet the conditions of operational safety. It is noteworthy that the greatest difference between joints made of steel from the HSS group and steel from the AHSS group is related to with fatigue life to the disadvantage of joints made of HSS steel. The final stage of the research was the impact toughness test, which was carried out at -20°C and 0°C. As in the previous test, the MAG joints with preheating were tested and marked as: Pz1, Pz2, Pz3. The results of the impact toughness tests are presented in Table 10.6.

Table 10.6

Impact toughness results

Symbol próbki	Materiał	KV (at -20° C)	KV (at 0° C)
Pz1	S960 QL	32	52
Pz2	DOCOL 1200M	49	61
Pz3	DOCOL 1400M	39	53

Source: Own study.

Based on the information in Table 13.6, it can be concluded that the impact toughness at 0° C is above the required value of 47 J. This means that the welded structure of the means of transport made of the tested materials with selected MAG process parameters will be characterized by resistance to cracking under dynamic loading. and therefore the safety of its use will be ensured. The best impact strength has a joint made of DOCOL 1200M steel, where the high second class of impact strength is met. High impact toughness values are related, among others, to with the amount of heat input for the steel grades to be welded and properly selected linear welding energy, which is influenced by the selected process parameters: welding speed and welding current. Thus, it can be unequivocally stated that appropriate bonding parameters were selected and applied to make the joints.

10.5. Summary

Increasingly used materials in the construction of means of transport are high--strength steels HSS and AHSS. These steels are dominated by a martensitic structure which does not correspond to good weldability. In order to obtain the correct joints with the best mechanical properties, it is very important to select the most important welding parameters (e.g. sheet bevelling, chemical composition of electrode wires, type of shielding gas, linear energy of welding, setting the preheating temperature, controlling the temperature of inter-stitching). For high-strength steel structures proposed in the construction of means of transport (e.g. for elements of a mobile landing) with sheets of different thickness, a detailed weldability analysis should be performed separately. Based on the presented research and analysis of the obtained results, it can be concluded that to obtain the correct joint from the tested steels with a thickness of 4 mm, it is recommended to use the MAG welding speed at the level of 330 mm / min and the use of preheating at the level of 105°C. All tested joints made of various types of high--strength steels showed good mechanical properties and met the requirements for materials, for example intended for mobile platforms. The recorded tensile strength values of the tested joints were clearly lower than those obtained for the native materials, while the determined immediate tensile strength was in all cases above 600 MPa. Thus, high-strength steel couplings can be used in the construction of means of transport. The joints have relatively good plastic properties, which was confirmed by the results of the bending and impact tests. The safety of the welded structure is confirmed by the high fatigue life of the tested joints and their high impact strength. Joints made of AHSS steel have significantly higher fatigue strength compared to the tested joint made of HSS steel. Based on the fatigue tests, it can be concluded that the most responsible welded structures of transport means should be made of steels from the AHSS group. The best weldability of all tested steel grades with a thickness of 4 mm has the DOCOL 1200M steel.

Acknowledgments

The article is related to the implementation of the COST project, CA 18223.

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MODERN MOBILITY: CHALLENGES AND DEVELOPMENT TRENDS

Summary

Modern mobility is a very broad concept. It covers transport issues, but also ecology, safety, accessibility or the life cycle of products. Society has come to expect from transport not only that people will be transported from place A to place B, but also that the environment will not be polluted, that the journey will take the shortest route and that it will be safe and comfortable. This makes the field of transport-related issues and problems very broad and constantly expanding.

The subject of determining the shortest routes for vehicles has been under consideration for many years. However, it is taking on a new significance as another variable in these considerations is the electric car or bus and, more specifically, the need to recharge it frequently. With the increasing popularity of electric vehicles come problems such as the availability of charging stations, longer charging times than refueling traditional combustion vehicles and shorter range. The shorter range is the main disadvantage of operating electric buses, which largely depends on the capacity of the traction batteries and the current energy consumption. This, in turn, depends on travel parameters, including driving times and speed profiles when travelling along the bus route. Analysis of the travel parameters allows an estimation of the typical energy consumption along the considered bus route and consequently allows an assessment of the suitability of the considered bus route for operation with electric buses.

Modern mobility also means the development of roads, especially urban tunnels, which protect city centers from traffic, noise and pollution. The increasing number of urban tunnels raises the need to analyses the safety of the users of these tunnels in the event of a fire outbreak. In an enclosed space such as a tunnel, a fire is always a huge challenge for people who have to evacuate it and for rescue teams.

The introduction of modern mobility systems into the existing spatial structures of a city can be a means for their redevelopment, modernization, revitalization and is a condition for building good accessibility of different social groups to important areas and facilities of a city. In turn, good transport accessibility is a condition for a just city.

Transport accessibility can be analyzed already at the neighborhood level in the context of appropriate public transport timetables, the location of stops or architectural barriers to reaching certain stops.

Also related to the theme of mobility are issues concerning vehicles and their audit systems. The use of weighing stations based on inductive loops is common. These provide detailed data on each passing vehicle. These data include information on vehicle length, number of axles, wheelbase, total weight, individual wheel and axle loads. Their appropriate configuration makes it possible to exclude vehicles that exceed the permissible standards, which can significantly improve road safety. In addition to external control, vehicle suspension diagnostics at vehicle weighing stations also play an important role in terms of driving safety and comfort.

The construction of modern vehicles depends on the ability to use innovative materials and processing technologies. New challenges include the use of lightweight alloys and new generation body steels. The main aim of using these materials is to reduce the weight of vehicles, thereby reducing energy consumption and increasing range. The search for materials to reduce the weight of vehicles is particularly important in view of emissions legislation, which requires the fitting of numerous additional components such as exhaust catalytic converters, particulate filters and additional exhaust components such as injectors. These components, on the one hand, significantly reduce harmful emissions and, on the other, contribute to the overall weight of the vehicle.

The current state-of-the-art vehicles are mainly electric cars, which have low emissions of traffic pollutants and are based on the latest technologies. However, when considering the nuisance of vehicles and transport systems, should only their use be considered? An analysis of the carbon footprint of electric vehicles relative to combustion vehicles at the manufacturing stage shows that the energy required to produce an electric car is 1.6 higher than that of its combustion counterpart.

The issues addressed in the monograph show how complex and multifaceted the topic of modern mobility is. The public's expectations of transport are enormous and concern several levels such as safety, ecology and accessibility.

NOWOCZESNA MOBILNOŚĆ: WYZWANIA I TRENDY ROZWOJOWE

Streszczenie

Nowoczesna mobilność jest pojęciem bardzo szerokim. Obejmuje zagadnienia związane z transportem, ale również z ekologią, bezpieczeństwem, dostępnością czy cyklem życia produktów. Społeczeństwo zaczęło oczekiwać od transportu nie tylko tego, że ludzie zostaną przewiezieni z miejsca A do miejsca B, ale także tego, że w czasie tego procesu nie zostanie zanieczyszczone środowisko, że ten przejazd nastąpi najkrótszą drogą, że będzie bezpieczny i komfortowy. Powoduje to, że obszar zagadnień i problemów powiązanych z transportem jest bardzo rozległy i ciągle się powiększa.

Tematyka wyznaczania najkrótszych tras pojazdów jest rozpatrywana już od wielu lat. Nabiera ona jednak nowego znaczenia, ponieważ w tych rozważaniach pojawia się kolejna zmienna, jaką jest samochód czy autobus elektryczny, a dokładnie konieczność jego częstego ładowania. Z coraz większą popularnością pojazdów elektrycznych wiążą się takie problemy, jak dostępność stacji ładowania, dłuższy czas ładowania niż tankowanie tradycyjnych pojazdów spalinowych oraz krótszy zasięg. Ten ostatni jest główną wadą eksploatacji autobusów elektrycznych, która w znacznym stopniu zależy od pojemności baterii trakcyjnych i bieżącego zużycia energii. Ono z kolei zależy od parametrów podróży, w tym od czasu jazdy i profili prędkości podczas przemieszczania się wzdłuż trasy autobusu. Analiza parametrów podróży umożliwia oszacowanie typowego zużycia energii na rozważanej trasie autobusowej, a w konsekwencji pozwala na ocenę przydatności rozważanej trasy autobusowej do eksploatacji z autobusami elektrycznymi.

Nowoczesna mobilność to także rozbudowa dróg w tym przede wszystkim tuneli, szczególnie miejskich, które chronią centra miast przed ruchem samochodowym, hałasem i zanieczyszczeniami. Coraz większa liczba tuneli miejskich rodzi potrzebę analizy bezpieczeństwa użytkowników tych tuneli na wypadek wybuchu pożaru. W zamkniętej przestrzeni, jaką jest tunel pożar to zawsze ogromne wyzwanie dla ludzi, którzy muszą się z niego ewakuować oraz dla ekip ratowniczych.

Wprowadzenie nowoczesnych systemów mobilności do istniejących struktur przestrzennych miasta może być środkiem do ich przebudowy, modernizacji,

rewitalizacji oraz jest warunkiem budowania dobrej dostępności różnych grup społecznych do ważnych obszarów i obiektów miasta. Z kolei dobra dostępność transportowa jest warunkiem sprawiedliwego miasta. Może być ona analizowana już na poziomie osiedla w kontekście odpowiedniego rozkładu jazdy komunikacji miejskiej, lokalizacji przystanków czy barier architektonicznych, utrudniających dotarcie do niektórych przystanków.

Z tematyką mobilności związane są również zagadnienia dotyczące pojazdów oraz systemów ich kontroli. Powszechne jest wykorzystywanie stacji ważenia opartych na pętlach indukcyjnych. Dostarczają one szczegółowych danych na temat każdego przejeżdżającego pojazdu. Dane te obejmują informacje o długości pojazdu, liczbie osi, rozstawie osi, masie całkowitej, naciskach poszczególnych kół i osi. Ich odpowiednia konfiguracja pozwala na wykluczenie z ruchu pojazdów, które przekraczają dopuszczalne normy, co może znacznie poprawić bezpieczeństwo ruchu drogowego., Na stacjach ważenia pojazdów, poza kontrolą zewnętrzną, istotną rolę z punktu widzenia bezpieczeństwa i komfortu jazdy odgrywa również diagnostyka zawieszenia pojazdów.

Budowa nowoczesnych pojazdów zależy od możliwości wykorzystania innowacyjnych materiałów i technologii przetwarzania. Nowe wyzwania dotyczą między innymi wykorzystania stopów metali lekkich i stali karoseryjnych nowej generacji. Głównym celem stosowania tych materiałów jest zmniejszenie masy pojazdów, a tym samym zmniejszenie zużycia energii i zwiększenie zasięgu. Poszukiwanie materiałów pozwalających na zmniejszenie masy pojazdów jest szczególnie istotne wobec przepisów dotyczących emisji spalin, które wymagają montowania licznych, dodatkowych podzespołów, takich jak: katalizatory spalin, filtry cząstek stałych, dodatkowe elementy układu wydechowego, np. wtryskiwacze. Elementy te z jednej strony znacząco ograniczają emisję szkodliwych substancji, a z drugiej przyczyniają się do zwiększenia całkowitej masy pojazdu.

Aktualnie, nowoczesne pojazdy to przede wszystkim samochody elektryczne, które w niewielkim stopniu emitują zanieczyszczenia komunikacyjne, a ich konstrukcja oparta jest na najnowszych technologiach. Czy jednak przy rozpatrywaniu uciążliwości pojazdów i systemów transportowych należy brać pod uwagę tylko ich użytkowanie? Analiza śladu węglowego pojazdów elektrycznych w stosunku do pojazdów spalinowych na etapie ich produkcji pokazuje, że energia potrzebna do wyprodukowania samochodu elektrycznego jest o 1,6 wyższa niż w przypadku jego spalinowego odpowiednika.

Zagadnienia poruszane w monografii pokazują jak bardzo złożony i wielowątkowy jest temat nowoczesnej mobilności. Oczekiwania społeczne wobec transportu są ogromne i dotyczą kilku płaszczyzn, takich jak bezpieczeństwo, ekologia czy dostępność.

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Nakł. 60 + 44	Ark. wyd. 15	Ark. druk. 12,25	Papier 80 g

Zam. 9/24
Monografia 1020

ISBN 978-83-7880-950-0
Wydawnictwo Politechniki Śląskiej

Series: Excellence Initiative - Research University

Silesian University of Technology

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