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Analysis of the Impact of Road Traffic Generated by Port Areas on the Urban Transport Network—Case Study of the Port of Gdynia

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Abstract: The paper's main aim is to present the impact on the city's road traffic generated by the Port of Gdynia's operations and propose the optimal solution for transport network development around the port. Firstly, the authors demonstrate a case study determining the impact of heavy goods vehicles (HGVs) generated by port facilities on local traffic. To this end, the average travel time of cars in the network on selected measurement sections is conditioned on the varying number of HGVs generated by the port. Next, based on the data obtained from the traffic monitoring system, PTV Vissim software is used as a modelling tool to analyse and assess the impact on local traffic. Finally, considering the analysis' results, the vulnerability of the transport network is discussed. The optimal solution for the transport network around the port's area is proposed. The paper is an extended version of the materials presented at the XIX Maritime Traffic Engineering Conference.

Keywords: transport modelling; microsimulation analysis; intelligent transport; vulnerability; transport networks

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1. Introduction

Seaports are within the scope of scientists from all over the world. Most research can find references to economics [1,2], and only a few papers focus on the effect of ports on the surrounding transport network [3]. Even then, this is often performed implicitly. For example, research presented in [4] discusses the role of the port in shaping the country's economy by discussing a port in Bangladesh. It is pointed out that the development of a port would positively impact the area where the ports are located.

However, the issues of navigating the access roads to the port were not addressed, and a significant course and cargo departure from the land port by road were omitted. Similarly, in [5], the authors focused on describing changes in the port infrastructure. In the analysed variants of modernisation, they consider increasing the throughput capacity from 64 million tons to 125 million tons. Although the analysis is very detailed, describing such details as the deepening of the port, quay, or breakwater renovation, similarly to the previously mentioned one, it does not present information about the effect on the existing road network leading to the port or what impact the enlarged port will have on the traffic volume. Interesting research on the combination of game theory and computer science in solving logistics problems in port areas has been published in [6]. However, it still only discusses the port area as a problem of throughput. The authors in [7] concluded that cities and ports occupy a vital aspect of the coast's social and economic landscape. It is crucial that port cities in the past developed simultaneously with the ports. The authors also emphasise that the town combines sea and waterways and plays a pivotal role in developing various modes of transport. A highly important publication [8] draws attention to the research carried out in developing the Klaipeda port, which showed that the port has a very busy road connection. The limited capacity of local roads leading to the port

can be a severe obstacle to the development of the port, and thus the flow of cargo. In the literature, there are studies on port cities in Germany [9], which shows the dynamic relationship between urban space and port space in the process of urban development in Europe, or, for example, in China [10], which shows the emergence of urbanised seaports, with the theoretical help of a formal economic geography model.

Gdynia, a port city, struggles with sharing infrastructure for transporting cargo and residents. Due to the need for more relevant research on the impact of road traffic generated by port areas on urban road traffic, we propose a microsimulation model and a case study of the Port of Gdynia, located in the northern part of Poland. The port is challenging because it is located in the central part of the city [11,12]. It even divides the city into a northern half and southern half. It is worthwhile undertaking research that addresses how to improve the current transport infrastructure, so that the traffic coming from the port does not negatively affect the entire network of the city of Gdynia.

This paper presents the relationship between the port and the city road network. To this end, a micro-simulation model is developed by applying the PTV Vissim tool [13–18] on a microscopic scale [16,19,20]. These results are then used to determine the vulnerability of the transport network. This, in turn, made it possible to identify the best solution for the problem of burdening Gdynia's transport network.

This way, we try to answer the research question, "how to better optimise and coordinate port and urban transport through network planning or management?".

Our results show how small increases in the number of vehicles generated by the port can significantly affect the performance of the road transport network. Thus, it affects the city's development and the level of service perceived by the inhabitants.

2. Materials and Methods

2.1. Modelling with PTV Vissim

The method of model building in the PTV Vissim software is described in the articles [21,22]. To carry out the analysis, as a case study of the impact of heavy goods vehicles on the urban transport network, a model was implemented that reflects the existing state in the example of the port city of Gdynia. Traffic caused by cars and HGVs mainly characterises the modelled area. Over the past few years, the city has also been encouraging residents to use public transport. Thus, there are bus lanes for public transport vehicles in the modelled section. To demonstrate the scale of the traffic volume on the road network from the model obtained from the local road administrator, Figure 1 shows the distribution of traffic on the roadway near the port areas.

The traffic volume in the sections in the port area is approximately 3500 vehicles per hour. The maximum intensity is up to 4000 vehicles per hour. It should be noted that the main flyover connecting the north and south of the city has only two lanes. There are some ramps and ascents in the third lane. Figure 1 shows the traffic flow around the port area.

The existing condition of the modelled network was compared to the increased volume of heavy goods vehicle traffic, resulting from travel to and from the port from 10% to 100% more HGVs. The model aimed to check the periods in which the freedom of movement would remain within the range, regarding operational reliability. Particular operating reliability limits for individual states were determined based on the existing state model.

To perform the described analysis, a simulation model was created using the PTV Vissim tool [23–25]. This model was implemented with data from the Gdynia Road and Greenery Authority in Gdynia and manually calculated data. The data come from the TRISTAR Intelligent Traffic Control System. Additionally, measured manually was the peak hours data to calibrate the model with the exact generic structure of the vehicles. Figure 2 shows example cars at one of the intersections.

An example of a transport network based close to the port area is the city of Gdynia. Road sections included in the model were Estakada Kwiatkowskiego with several junctions.

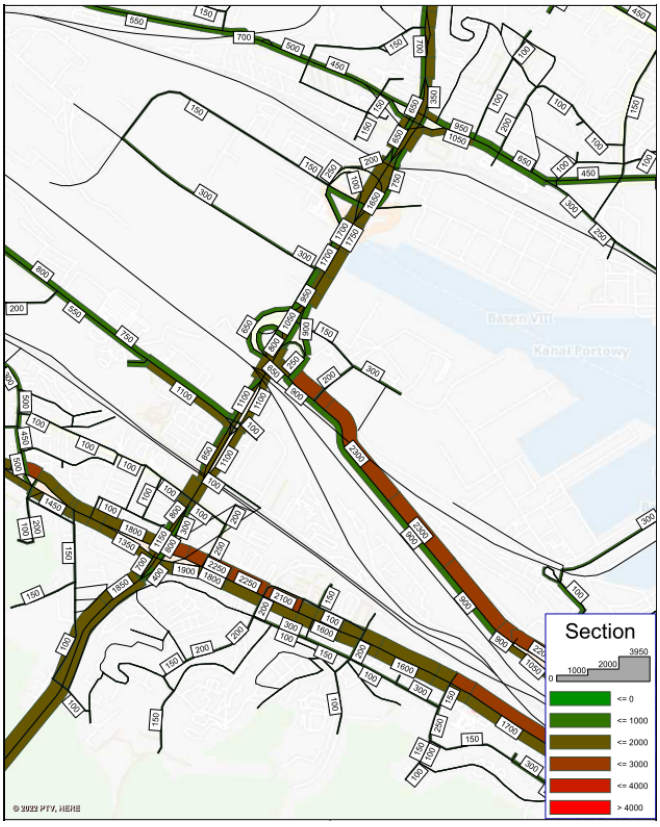


Figure 1. Traffic Flow during PM peak—Gdynia [Source: the model was made available by the Gdynia City Hall—road administration].

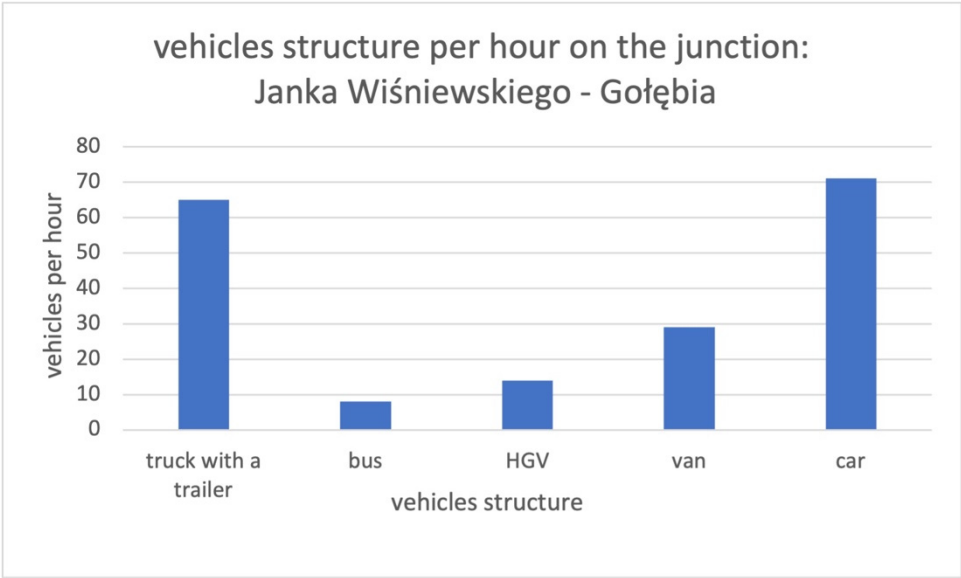


Figure 2. Structure of the vehicles on junction Janka Wiśniewskiego—Gołębia, (P—pedestrian, T—trams, M/R—motorbike/bike, C/P—a truck with a trailer, A—bus, C—HGV, F—van, O—car [veh/h]).

2.2. Graph Theory Approach to the Vulnerability of Transportation Networks

According to [26], we considered the connected, simple, undirected graph $G = (V, E)$, where V or $V(G)$ is the set of vertices (nodes), and E or $E(G)$ is the set of edges (arcs). Some basic graph theory definitions should be introduced to understand the terms used in this article. The collection of all adjacent vertices to vertex $v \in V$ in G is called the

neighbourhood and is denoted by $N_G(v)$ or $N(v)$. The close neighbourhood of this vertex is defined as $N_G(v) \cup \{v\}$ and denoted by $N_G[v]$ or $N[v]$. The other primary essential parameter for graphs is the degree of vertex $v \in V$, which is defined as the number of vertices in $N_G(v)$ and denoted by $deg(v)$. Additionally, a set D $\subseteq$ V(G) is a dominating set of graphs, G, for any $v \in V(G)$, where either $v \in D$ or $N_G(v) \cap D = \emptyset$. At the same time, the minimum cardinality of a dominating set of graphs, G, is called a domination number of G and is denoted as γ(G). Furthermore, a set $X \subseteq E(G)$ is called the edge-dominating set of graph G if every edge not in X has a neighbour in set X. The cardinality of a minimum-edge-dominating set is called the edge-domination number of a graph, G, and is denoted by $\gamma'(G)$.

Essential to these definitions, we define a bondage-connected number $b_c(G)$ of nonempty graph, G, as the minimum cardinality among all sets of edges E for which $\gamma(G - E) > \gamma(G)$ and graph $G - E$ are connected [26].

Bearing in mind the above definitions, we can further define the basic critical parameters of the transport network under consideration, such as [26]:

- Number of critical nodes described by a domination number;
- Number of critical edges described by an edge-domination number;
- Topological (structural) vulnerability of transport network described by a bondage-connected number;
- Node-bottlenecks of transport network described by dominating set;
- Arc-bottlenecks of transport network described by an edge-dominating set.

3. Results

Using the PTV Vissim tool, the results regarding the existing state were obtained to determine the impact of heavy goods vehicles on the urban road network. The first analysed variant is the current state of a section of the road network. Named in the model as variant 0. The following parameters were analysed:

- Average travel time;
- Queues of vehicles;
- Average speed;
- Delays.

Average travel time and speed measurements were measured at three locations on the road network. These places are essential due to the location of the terminals in the city. The measurement in Section 1 is 1434 m long, in Section 2 is 412 m long, and in Section 3 is 1600 m long. All sections are shown in Figure 3.

After the simulation, the measurement results are as follows:

Section 1 has both a moderate average speed and an average travel time over the entire measurement period. Average travel time ranges from 78 to 88 s. The average speed does not drop below 60 km/h. The first section is characterised by traffic from residential districts located in the northern part of the city to the city centre or the Tri-City ring road.

Section 2 runs in the opposite direction to Section 1. Thus, the Tri-City Ring Road to the city's northern districts provides a direct connection to container terminals. According to measurements, the highest network load is in the afternoon rush hour. The average speed drops from 70 km/h to 16 km/h. The average driving time increases to 140 s from 20 s.

Section 3 runs from the mass terminals to the Tri-City Ring Road. Like Section 1, there are no significant fluctuations in the measurement results during the entire period. The average travel time varies from 120 to 140 s, and the average speed ranges from 40 km/h to 50 km/h. The graphs below show the results of the simulation measurements. In this paper, all measured values come from the simulations, variant 0, and all scenarios. They are called variants. The variant is 0 for the actual state, and variants from 1 to 10 represent additional HGVs from 10 to 100. Figures 4–6 show the results.

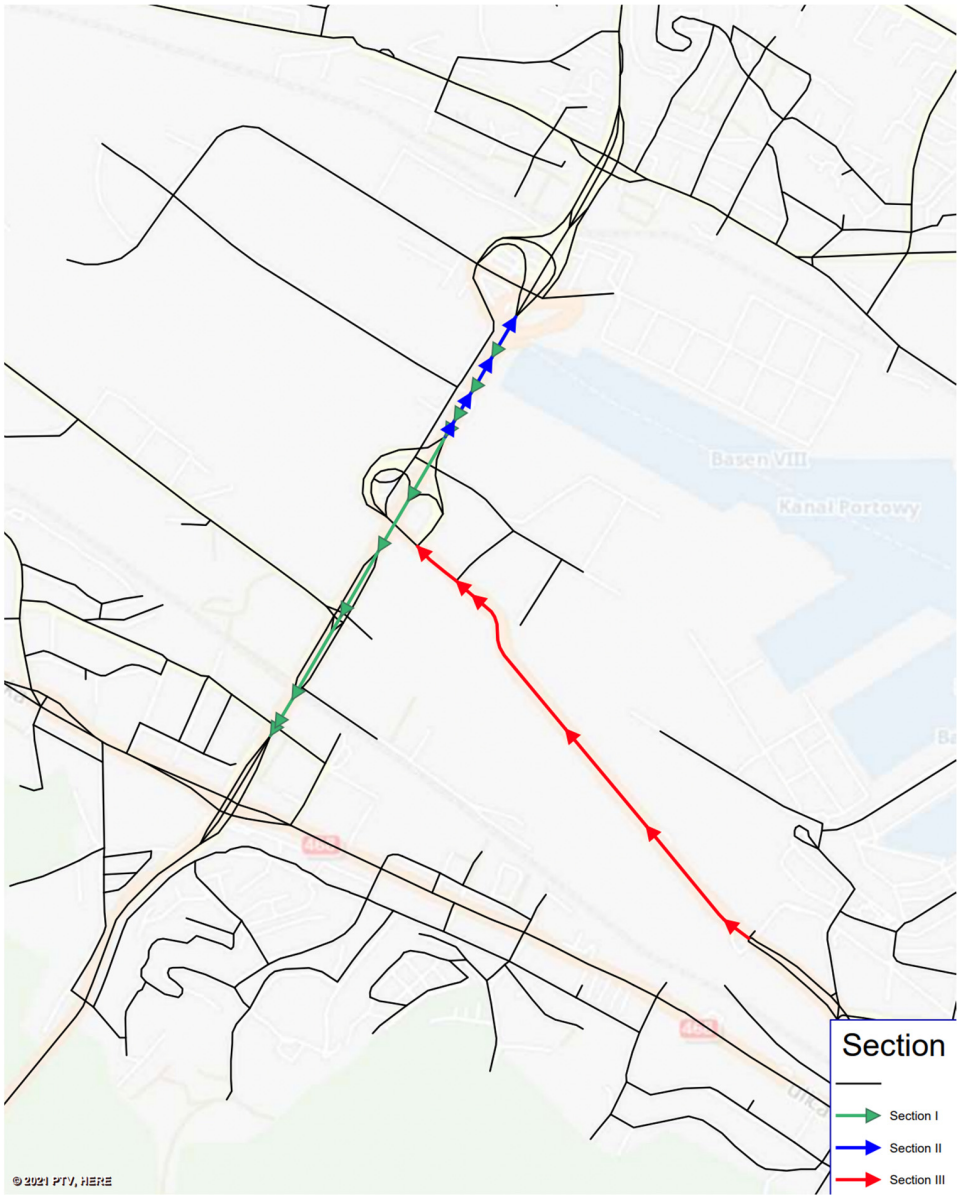


Figure 3. Sections 1–3.

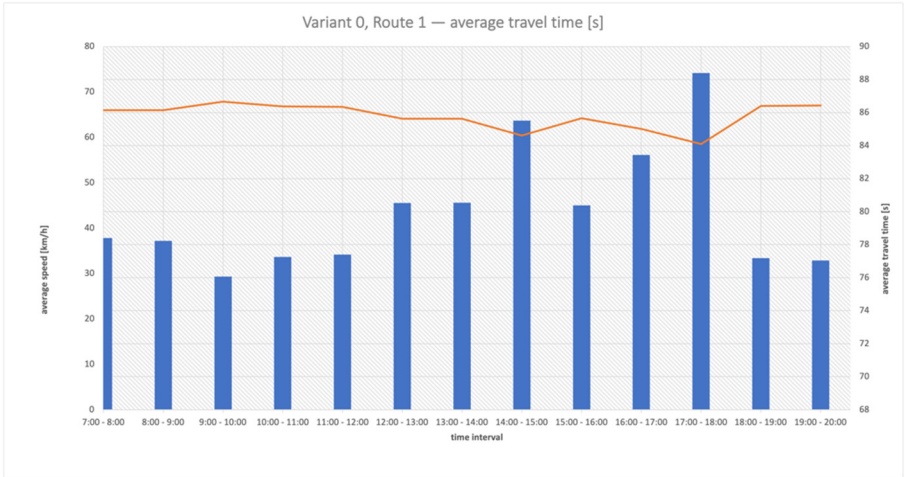


Figure 4. Variant 0; Section 1—average travel time [s].

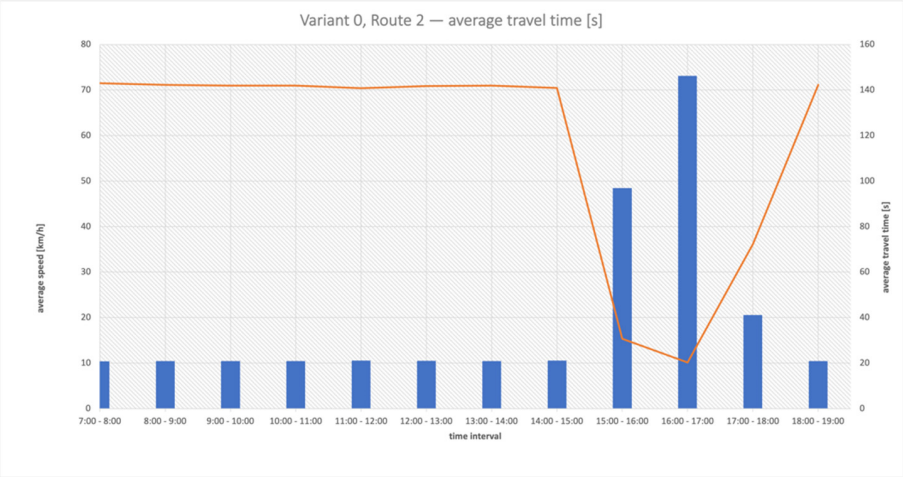


Figure 5. Variant 0; Section 2—average travel time [s].

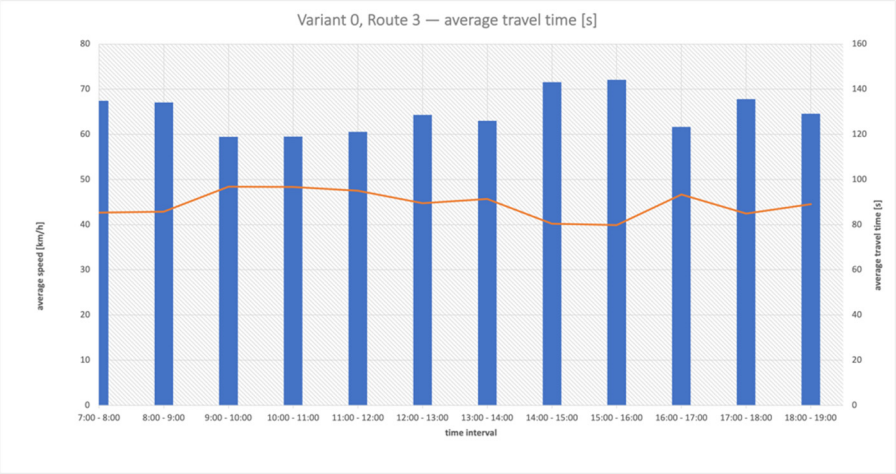
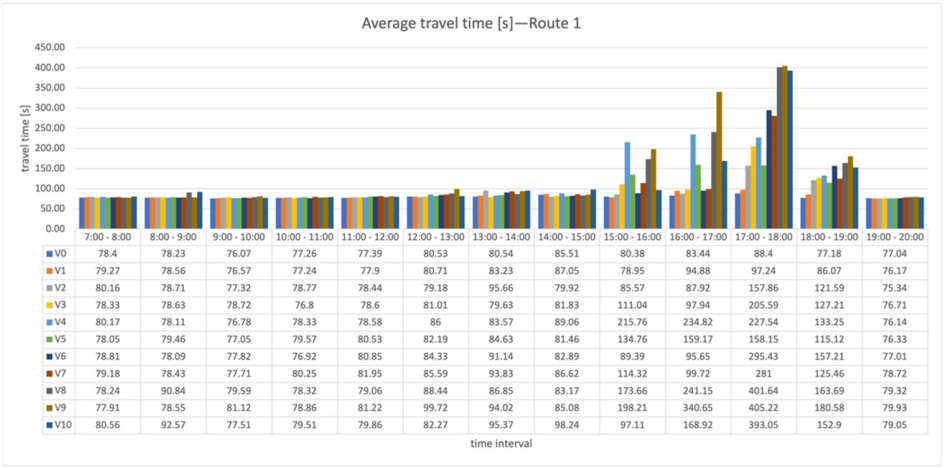


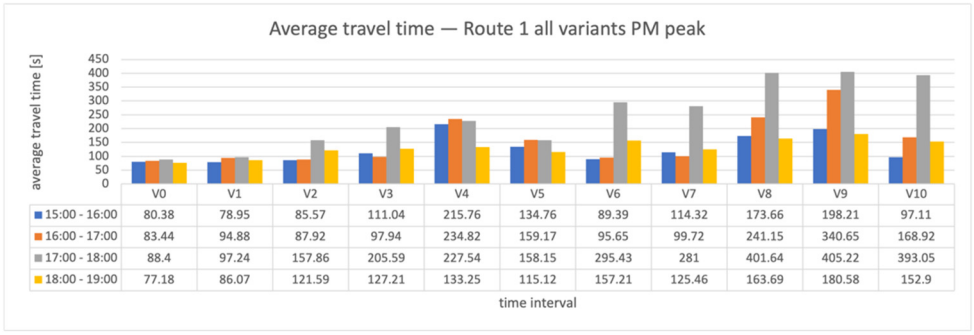
Figure 6. Variant 0; Section 3—average travel time [s].

Figures 7 and 8 show the simulation results for variant 0—representing the actual state. The different parts of the analysis present variants from 1 to 10. Each variant increases the number of heavy goods vehicles by 10% (from 10% to 100%) generated at points corresponding to containers and mass terminals in the city.



	7:00 - 8:00	8:00 - 9:00	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00	19:00 - 20:00
V0	78.4	78.23	76.07	77.26	77.39	80.53	80.54	85.51	80.38	83.44	88.4	77.18	77.04
V1	79.27	78.56	76.57	77.24	77.9	80.71	83.23	87.05	78.95	94.88	97.24	86.07	76.17
V2	80.16	78.71	77.32	78.77	78.44	79.18	95.66	79.92	85.57	87.92	157.86	121.59	75.34
V3	78.33	78.63	78.72	76.8	78.6	81.01	79.63	81.83	111.04	97.94	205.59	127.21	76.71
V4	80.17	78.11	76.78	78.33	78.58	86	83.57	89.06	215.76	234.82	227.54	133.25	76.14
V5	78.05	79.46	77.05	79.57	80.53	82.19	84.63	81.46	134.76	159.17	158.15	115.12	76.33
V6	78.81	78.09	77.82	76.92	80.85	84.33	91.14	82.89	89.39	95.65	295.43	157.21	77.01
V7	79.18	78.43	77.71	80.25	81.95	85.59	93.83	86.62	114.32	99.72	281	125.46	78.72
V8	78.24	90.84	79.59	78.32	79.06	88.44	86.85	83.17	173.66	241.15	401.64	163.69	79.32
V9	77.91	78.55	81.12	78.86	81.22	99.72	94.02	85.08	198.21	340.65	405.22	180.58	79.93
V10	80.56	92.57	77.51	79.51	79.86	82.27	95.37	98.24	97.11	168.92	393.05	152.9	79.05

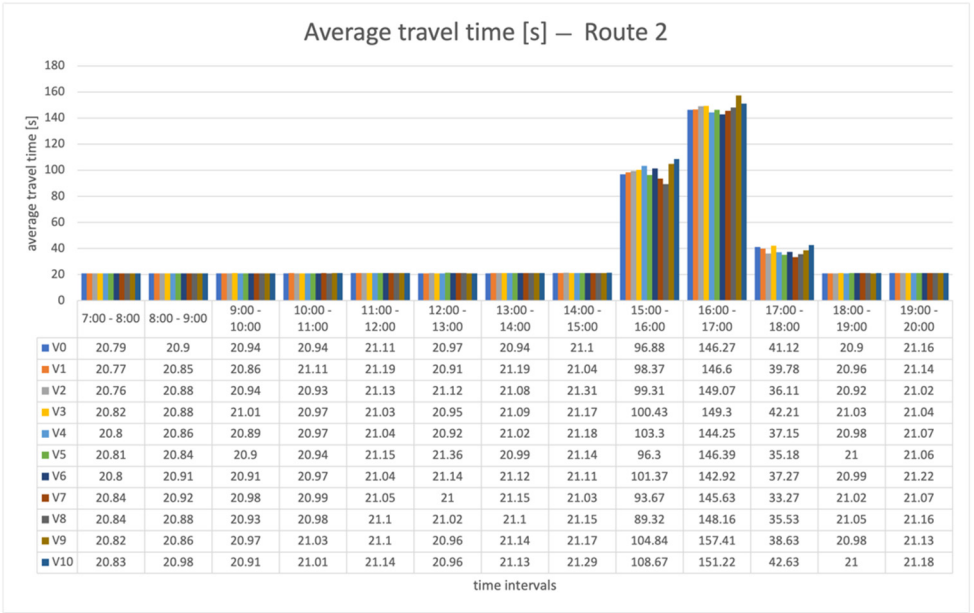
Figure 7. Average travel time; Section 1—all variants.



	V0	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
15:00 - 16:00	80.38	78.95	85.57	111.04	215.76	134.76	89.39	114.32	173.66	198.21	97.11
16:00 - 17:00	83.44	94.88	87.92	97.94	234.82	159.17	95.65	99.72	241.15	340.65	168.92
17:00 - 18:00	88.4	97.24	157.86	205.59	227.54	158.15	295.43	281	401.64	405.22	393.05
18:00 - 19:00	77.18	86.07	121.59	127.21	133.25	115.12	157.21	125.46	163.69	180.58	152.9

Figure 8. Average travel time; Section 1—all variants—PM peak.

Referring to the results obtained from the microsimulation for the first section, the most significant changes will occur with a 40% increase in the number of heavy goods vehicles from the generating sites. The analysed average travel time for Section 1 will extend during the afternoon peak, which is noticeable in Figure 9. To the analysed afternoon peak between 15:00 and 19:00, the first significant increase in travel time can be noticed for all variants already at a 30% increase in the number of heavy goods vehicles. On the other hand, with a 40% increase in the number of trucks, there is an increase to over 200 s compared to less than 80 s in the case of variant 0 for three hours of the afternoon rush. The longest average travel time of about 400 s occurs when the number of heavy goods vehicles at generator sites is increased by 80% or more. Detailed changes in trip duration in the afternoon rush hour are shown in Figure 9.



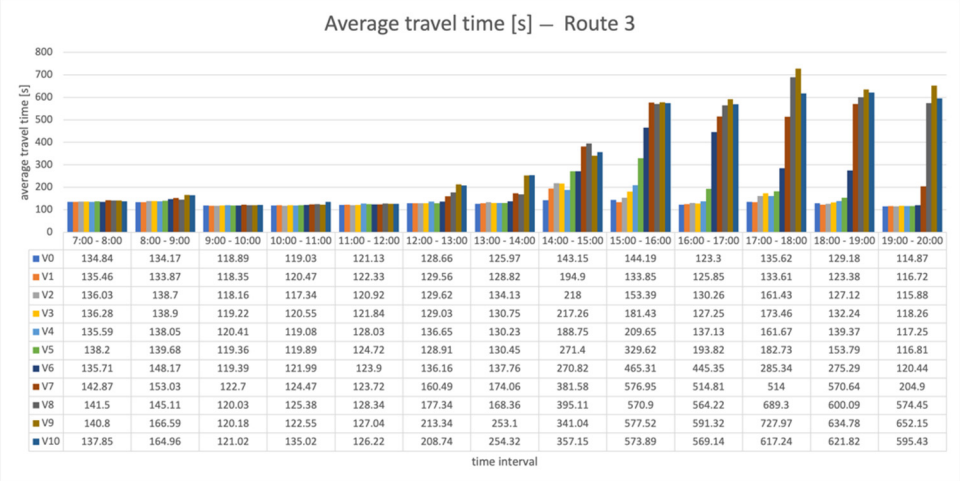
	7:00 - 8:00	8:00 - 9:00	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00	19:00 - 20:00
V0	20.79	20.9	20.94	20.94	21.11	20.97	20.94	21.1	96.88	146.27	41.12	20.9	21.16
V1	20.77	20.85	20.86	21.11	21.19	20.91	21.19	21.04	98.37	146.6	39.78	20.96	21.14
V2	20.76	20.88	20.94	20.93	21.13	21.12	21.08	21.31	99.31	149.07	36.11	20.92	21.02
V3	20.82	20.88	21.01	20.97	21.03	20.95	21.09	21.17	100.43	149.3	42.21	21.03	21.04
V4	20.8	20.86	20.89	20.97	21.04	20.92	21.02	21.18	103.3	144.25	37.15	20.98	21.07
V5	20.81	20.84	20.9	20.94	21.15	21.36	20.99	21.14	96.3	146.39	35.18	21	21.06
V6	20.8	20.91	20.91	20.97	21.04	21.14	21.12	21.11	101.37	142.92	37.27	20.99	21.22
V7	20.84	20.92	20.98	20.99	21.05	21	21.15	21.03	93.67	145.63	33.27	21.02	21.07
V8	20.84	20.88	20.93	20.98	21.1	21.02	21.1	21.15	89.32	148.16	35.53	21.05	21.16
V9	20.82	20.86	20.97	21.03	21.1	20.96	21.14	21.17	104.84	157.41	38.63	20.98	21.13
V10	20.83	20.98	20.91	21.01	21.14	20.96	21.13	21.29	108.67	151.22	42.63	21	21.18

Figure 9. Average travel time; Section 2—all variants.

In the case of Section 2, there are no significant changes in the average travel time through the measuring section. This section is already crowded between 15:00–17:00, so it cannot pass any more cars, and they appear in the form of queues of vehicles at further intersections in the road network. The results of all variants for the road section are shown in Figure 10.

In the case of Section 3, similarly to Section 1, changes in the average travel time through the measuring section occur in the afternoon and evening hours from 3:00 p.m. to 8:00 p.m. Between 3 p.m. and 4 p.m., an increase in the average travel time to over 450 s should be noted, compared to 130 s in variant 0, as well as in terms of increasing the

number of heavy goods vehicles at generator points by 60%. When increased by 70% and more, the time increases to more than 500 s. It can be seen from the simulation results that if the number of heavy goods vehicles is increased by 80%, the cars will travel the measuring distance in the afternoon rush in about 600 s. The number of cars and the time losses will be so great that vehicles will become queued at previous intersections in the road network. Changes in the average travel time through the measurements discussed in Section 3 can be observed in Figure 10.



	7:00 - 8:00	8:00 - 9:00	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00	19:00 - 20:00
V0	134.84	134.17	118.89	119.03	121.13	128.66	125.97	143.15	144.19	123.3	135.62	129.18	114.87
V1	135.46	133.87	118.35	120.47	122.33	129.56	128.82	194.9	133.85	125.85	133.61	123.38	116.72
V2	136.03	138.7	118.16	117.34	120.92	129.62	134.13	218	153.39	130.26	161.43	127.12	115.88
V3	136.28	138.9	119.22	120.55	121.84	129.03	130.75	217.26	181.43	127.25	173.46	132.24	118.26
V4	135.59	138.05	120.41	119.08	128.03	136.65	130.23	188.75	209.65	137.13	161.67	139.37	117.25
V5	138.2	139.68	119.36	119.89	124.72	128.91	130.45	271.4	329.62	193.82	182.73	153.79	116.81
V6	135.71	148.17	119.39	121.99	123.9	136.16	137.76	270.82	465.31	445.35	285.34	275.29	120.44
V7	142.87	153.03	122.7	124.47	123.72	160.49	174.06	381.58	576.95	514.81	514	570.64	204.9
V8	141.5	145.11	120.03	125.38	128.34	177.34	168.36	395.11	570.9	564.22	689.3	600.09	574.45
V9	140.8	166.59	120.18	122.55	127.04	213.34	253.1	341.04	577.52	591.32	727.97	634.78	652.15
V10	137.85	164.96	121.02	135.02	126.22	208.74	254.32	357.15	573.89	569.14	617.24	621.82	595.43

Figure 10. Average travel time; Section 3—all variants.

4. Discussion

The applied solution involves the preparation of a detailed model on a microscopic scale. Because each infrastructure element and each road user influences the simulation results, a tremendous amount of input data should be considered.

This model would show even more accurate results if equipped with modules of an adaptive traffic control system and not based on fixed-time programs. However, access to this type of connection is impossible for people who are not road managers. The presented model has been correctly calibrated and validated against the GEH [21,27] statistics. Thus, the results obtained are probable and possible to consider. Due to the linear infrastructure in the analysed city, road users who want to get to the northern districts of the town are forced to share the infrastructure with heavy goods vehicles. Constructing a new road with parameters like the existing one would result in a completely different distribution of road traffic. In this analysed case, drivers do not have alternatives. Thus, the road network in the vicinity of the port and the entire city of Gdynia is vulnerable to congestion. It, in turn, translates into the so-called carbon footprint. Therefore, it is of great importance for the traffic volumes indicated in the simulation model presented in Section 3. In addition, public transport loses its efficiency and profitability in the event of congestion on its routes.

Let us discuss the level of vulnerability of the transport network as it stands and after the construction of the road connecting the port with the Chylonia junction. Figure 11 represents the simplified graph theory [26] model of the road network given in Figure 1.

Considering the domination theory in the graphs presented in Section 2, the vertices "City Centre" and "Morska-Estakada" constitute the minimum dominating set. Thus, the domination number is equal to 2. It means that both nodes are critical from an urban road network point of view. They are heavily loaded and, therefore, prone to congestion—as evidenced by the daily rush hours in Gdynia. Moreover, they are the only nodes through which heavy goods traffic from the port may be directed to Tri-City Bypass.

If, for the smallest domination set chosen in this way, we remove the edge between the nodes "Morska-Estakada" and "Gdynia Chylonia", then it will be necessary to add the last vertex to the smallest dominating set, and thus increase the domination number to 3.

It means that the topological vulnerability of this network, described by parameter bc(G), equals 1. Therefore, the network presented in Figure 11 is vulnerable to disturbances.

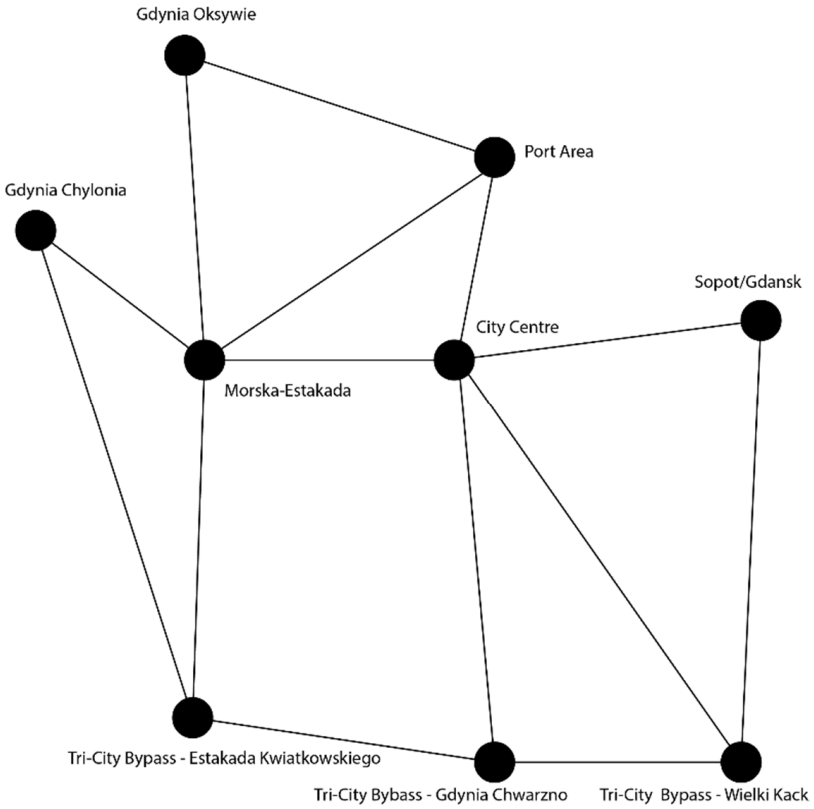


Figure 11. Graph theory model of the analysed road network in Gdynia.

Now, let us consider an edge-dominating set and edge-domination number for the network presented in Figure 12. Arcs can constitute the minimal edge-dominating set: {"City Center"; "Tri-City Bypass—Wielki Kack"}, {"Morska-Estakada"; "Tri-City Bypass—Estakada Kwiatkowskiego"}, and {"Port Area"; "Gdynia Oksywie"}. The minimum edge-domination number equals 3. The edge-dominating set describes three arcs, which are critical for the Gdynia urban road network. Consequently, blocking one of these connections will result in the necessity to transfer all traffic generated in the port to the "City Centre" and "Gdynia Chylonia" nodes.

However, for a long time, there have been plans to connect the port directly with the Tri-City bypass at the Chylonia junction by "Red Road" for a long time. Figure 12 shows the completed model of the road network in Gdynia after completing the plans.

In this case, the dominating set can still be the same. However, the bondage-connected number goes up to two. It means that the network's resilience to disruptions of individual routes, especially those departing from the port, is improved. In other words, the flow of heavy vehicles from the port could be spread over many alternative routes in the event of adverse events. Thus, there is a chance to improve the parameters assessed during the simulation. Therefore, travel times are likely to be shorter, average travel speeds will increase, and thus the capacity of the transport network will grow. Both the port and the city take advantage of this. In the first case, this will allow for a further increase in transhipment. Additionally, in the city's case, the inhabitants' quality of life will improve by reducing the negative impact of transport on the environment (reducing the carbon footprint) and improving the efficiency of public transportation.

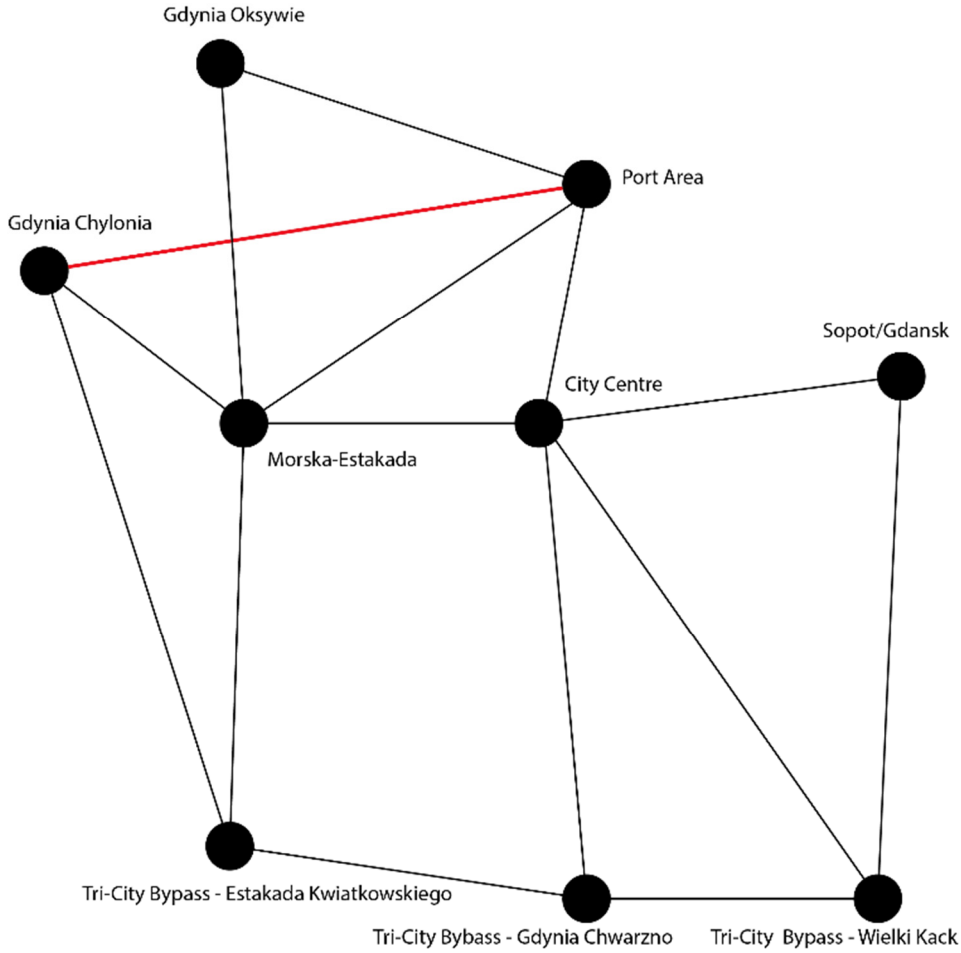


Figure 12. Graph theory model of the analysed road network in Gdynia with "Red Road".

5. Conclusions

The conducted research gives feedback about the consequences for the relationship between the city and the port. The main disadvantage of the port part is the traffic congestion. In this way, we can say how travel time could change by increasing the number of cars generated by the port.

The presented analysis shows that an increase in the number of heavy goods vehicles by as much as 40% on an hourly basis had a significant impact, especially during the afternoon rush hours.

This increase should be treated as the limit above which no heavy goods vehicles should arrive on the analysed section of the network. The road networks with a composite structure of vehicle types—as in the investigated case, where city traffic is constantly intertwined with traffic generated by the port—are challenging to manage. However, the city authorities are happy with the increase in transhipment at the port. However, they worsen the traffic conditions for residents. Therefore, the city authorities should:

- Start considering alternative options, for example, a dry port outside the city limits or increasing the percentage of cargo handling by rail.
- Ensure the road network from the port area is equipped with an alternative route for the inhabitants or collective transport.
- Develop the rail connections in the northern part of the city so they are more useful for the citizens.

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