



Article

Analysis of Pollutant Emissions on City Arteries—Aspects of Transport Management

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Abstract: The aim of the study is to present a methodology for analyzing pollution emissions in a medium-sized city using modern traffic simulations in the aspect of minimizing exhaust emissions. The scope of the research and the methods of analysis used differ from those applied in big cities projects that can be found in the literature, Therefore the progressive elaboration model has been applied methodically to formulate and carry out the feasibility study. To perform microscopic traffic simulations, the software Simulation of Urban Mobility (SUMO—German Aerospace Center (DLR), Berlin, Germany) was applied. Thanks to the simulations, changes in traffic organization were accurately identified in the context of pollution emissions before they were implemented. The proposed approach allows a smooth flow of vehicles and a reduction of exhaust emissions. The experiments, supported by visual modelling of traffic with respect to pollution emissions, were performed on one of the main arteries of the city of Czestochowa (Poland). The results were used to explain the benefits of planned roadworks and convince the city government of the necessity to modernize the communication network.

Keywords: traffic analysis; pollution emission; Simulation of Urban Mobility platform



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1. Introduction

The transportation problems of cities are increasingly common phenomena that affect not only the most populated agglomerations. It is a result of the increased mobility of the population as well as the economic development of cities, including in particular the greater number of passenger cars and other means of public transportation. All these factors cause growing problems related to traffic capacity on the main arteries of cities, in particular rising pollution emission.

In the paper a methodological approach to analyzing and reducing pollution emission through improvement of traffic organization on the main arteries of a medium-sized city (around 200,000 inhabitants) is presented using modern methods of traffic simulation, with a particular focus on exhaust emissions. Most traffic pollution emission studies are focused on big cities environment where the scope of research is very large and human as well financial resources are considerable. This is not the case with medium-size cities. Because of the specific context and limited funds politicians and governors should find adequate and methodically correct approaches to tackle the problem. Among the numerous approaches to study pollution emissions, the progressive elaboration model can be considered the best

choice [1–3]. In practice, it means to begin a project with the essential requirements, and after the approval of the first outcomes, refine the requirements when more accurate estimates become available, and extend the scope of the research. The progressive elaboration is a kind of waterfall model, well-known in the scientific literature, where the project is divided into sequential phases which are executed depending on the deliverables of the previous one. In this research, taking into consideration the complexity of the case study and limited available resources, the progressive elaboration model has been applied. For this reason, both the scope of the research and the methods of analysis used differ from those that can be found in the literature.

Unfortunately, the existing urban transportation networks of medium-sized cities are not prepared to handle an increased number of road users. This is mainly due to the present limitations of urban roads in terms of traffic capacity, as a result of which urban roads are usually unprepared to handle increased traffic volume in rush hours, or external factors occur, such as road accidents, failures or road repairs. It should be noted that the medium-sized cities in general do not possess an intelligent transportation systems to control the traffic. Therefore the sources of information are usually very limited. Analyzing the literature on the subject, it was noticed that there was no comprehensive research in the aspect of communication problems occurring in medium-sized cities, especially the negative effects of environmental impact. Traffic capacity issues result in a range of negative effects, such as traffic jams, which decrease road safety and reduce the comfort of using the available road infrastructure by increasing travel time, which is directly linked to a negative impact on the environment. Congestion is the main factor causing increased exhaust emissions as a result of vehicles moving slowly and frequently accelerating and stopping. Additional amounts of produced exhaust are released into the air, raising the level of pollution of the environment, contributing to a direct, negative impact on human health. It should also be stressed that a reduction in the traffic quality in a city negatively impacts the city's value and attractiveness.

Traffic simulations help to make the right decisions concerning traffic organization, reduce the number of incorrect and capital-intensive solutions designed to improve urban traffic capacity, and at the same time allow the pollution balance to be maintained. Before implementing changes to road infrastructure, it is necessary to measure the infrastructure's effectiveness, and the cost effectiveness of particular implementations in addition to positive variants for exhaust emission.

The structure of the paper is as follows. After a review of the relevant literature, the following sections of the paper define the aim and specificity of the undertaken study and describe successive steps of the analysis using concrete numerical data. The report presents traffic simulation models in terms of their functions, limitations and application in medium city. In determining the scope of the analysis, the limited financial resources were taken into account, which were much smaller compared to traffic research carried out in large metropolises—therefore the study was deliberately focused on the areas of the city with the highest pollution levels: on the transport arteries. The last part of the paper recommends directions for improvements and changes to the transport infrastructure.

2. Literature Review

Numerous studies point out that urban infrastructure is not adapted to the dynamically increasing number of vehicles [4–6]. This is manifested in air quality limit values being exceeded, of those established in the regulations of the European Union and World Health Organization [7]. In many developed countries in the world, road transport is the main source of pollutant emissions. Cars generate carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM). According to the Intergovernmental Panel on Climate Change (IPCC), global greenhouse gas emissions are estimated to increase by 25–90% between 2000 and 2030. Harmful carbon dioxide (CO₂) is also projected to increase by 40–110%. Estimating the exact results is possible due to the exact quantitative values of the impurities [8].

This problem affects different areas in cities to a varying extent depending on the proximity of roads with lower or higher traffic volume [9]. There are many ways of reducing traffic volume in the central spots in cities by effectively increasing traffic capacity. For that reason, a city's artery has been selected as the area of the analysis. Pollution emissions depend not only on the increasing traffic volume, but also on vehicles' technical efficiency, fuel quality, the condition of the road surfaces, tunnels, intersections, etc. [10–13]. Every vehicle travelling around a city has to meet appropriate exhaust emission standards in accordance with the legal regulations applicable in a given city. The European Union introduced regulations concerning pollution emissions from motor vehicles with emission standards Euro 5 and Euro 6 for light vehicles and Euro 6 for heavy vehicles. Due to the simulator's limitations, in our calculations we limited the measurements to those types of vehicles. In doing so, we were aware that the estimation of the pollution level may be too optimistic. Therefore, in the conclusions of the analysis we arbitrarily increased the pollution level by 10%. The above-mentioned regulations are included in the following legal acts: regulation No. 715/2007 of the European Parliament and Council regulation No. 692/2008 of European Commission implementing regulation No. 715/2007 of the European Parliament and Council and in rules [14,15].

An important issue is the level of a vehicle's fuel consumption and the amount of pollution a vehicle releases into the atmosphere [16]. Exhaust emissions from passenger cars were presented among others in studies conducted by the Institute of Internal Combustion Engines of Poznan University of Technology, Poznan (Poland), which examined real-time pollution emissions for many groups of vehicles [17]. There were also studies and comparative analyses of exhaust emissions from vehicles at intersections [18].

The air quality in cities has a direct impact on human health and life, therefore it is important to increase public awareness of this topic. Air pollution contributes to numerous civilization diseases, such as cardio-vascular diseases or respiratory diseases to name a few [19,20]. 90% of harmful benzene is emitted into the atmosphere from anthropogenic sources, of which the largest contributors are: means of transport (80–85%), the oil and exploration industry (up to around 7.5%), chemical industry (up to around 13%) and municipal power engineering (up to around 7%) [21–25]. The development of air quality improvement standards should become a priority for effective urban management.

Two types of models designed to assess air quality are distinguished: physical and mathematical models [26–28]. The multi-scale simulation of cities was developed on the basis of the traffic emission model, climate simulation and urban public space. Assessment of the transport infrastructure in cities is possible thanks to the conducted analysis and simulation [29]. The impact of transportation in cities on the environment is calculated based on the traffic volume of individual vehicles emitting a certain amount of pollution [30,31]. Traffic simulation is based on three categories: microscopic modeling, macroscopic modeling and mesoscopic modeling, thanks to which traffic planning can be reliably applied in the studied areas [32].

Currently, exhaust emissions and the concentration of harmful compounds are monitored in real time by means of various online and offline tools [33,34]. Air quality management and monitoring are analyzed with the aim of designing new, alternative solutions to improve air quality and eliminate emission sources in an urban community [35–38]. Despite the use of very ecological solutions, transport is still the main source of air pollution and noise. [39] Atmospheric pollution in cities is mainly caused by transport. Reduction is possible after reliable measurements and obtaining information on the distribution and nature of these pollutants. Computer simulations of transport pollution are determined on the basis of spatial and temporal data. There are many variables, including the time of day, change of wind direction, changes in traffic, which significantly affect the simulation results.

There are many systems for the microscopic simulation of traffic flow of urban road networks, e.g., AIMSUN, Barcelona, Spain, GERTRUDE SAEM, Bordeaux, France, TRANSIMS, Peek Traffic, Amersfoort, Netherlands, SUMO, VISSIM, PTV, Karlsruhe, Germany. Most of them offer similar features of modeling, simulation and traffic analysis. The choice

of SUMO was founded on the interesting features of the simulation platform, notably the easy-to-use GUI, open source license and reach documentation [40].

SUMO is conceived to simulate a traffic road network of the size of a city. As the simulation is multi-modal, adequate knowledge of vehicle speed is necessary to estimate traffic flow, that influences vehicle exhaust emissions and fuel consumption which are strongly dependent on speed. Therefore, the estimation of the pollutant emissions from road transport requires an information about vehicle velocity on each road, knowing a travelers' origin-destination matrix. In microscopic simulation every vehicle is modelled individually and has a certain place and speed. Each second, these values are updated in relation to the vehicle ahead and the street network. The simulation of vehicles is time-discrete and space-continuous. In the project, the circulation and moving vehicles at a given moment were obtained by observers by counting vehicles. That was a very time-consuming task. However by restricting the model to the artery intersections, the survey and the runtime of the solving of the model were significantly reduced.

The traffic simulation model is strongly related to the pollutant emission model. In the literature two major emission model classes can be found:

- “inventory” emission models that include data for the major portion of the vehicle emission classes; their input usually includes a vehicle population composition and the amount of driven distance, optionally also the average speed or an abstract traffic state.
- “instantaneous” emission models that simulate a single vehicle's emission, which propose a further distinction into emission maps, regression-based models, and load-based models.
- Pollution models incorporate data from traffic models, urban road structure, and vehicle specification. It should be noted that not all available models cover all pollutants emitted by road traffic. Therefore the pollutants assumed to be needed should be defined. In SUMO public version offers the following emission models:
 - Handbook Emission Factors for Road Transport (HBEFA), which provides emission factors for all current vehicle categories (PC, LDV, HDV and motor cycles), each divided into different categories.
 - PHEMlight, a derivation of the original Passenger Car and Heavy Duty Emission Model (PHEM), is an instantaneous vehicle emission model. PHEM is based on an extensive European set of vehicle measurements and covers passenger cars, light duty vehicles and heavy-duty vehicles, from city buses up to 40 ton semi-trailers.

Within the SUMO program it possible to model the emissions of CO, CO₂, NO_x, PM_x, and HC. CO₂ emissions are nearly 1:1 proportional to fuel consumption. Fuel consumption is mainly influenced by two factors: a) the amount of work the engine has to deliver to run the vehicle and its subsystems over a certain distance (e.g., road section) and b) the operational conditions of the engine and of the exhaust after treatment, which defines the efficiency of these components. CO₂ and NO_x are not sensitive to speed in the velocity range of about 40 km/h to 80 km/h. Driving conditions, particularly speed, were poorly known, in particular regarding time of travel within the urban network. Driving behaviour, acceleration and deceleration are uniformly defined.

Today, modern technologies are used that combine accurate traffic data with Intelligent Traffic Systems (ITS) [41]. Systems already in use at the planning stage should take into account the social benefits of smaller and larger investments in urban infrastructure in cities of all sizes [42].

3. Aim of the Study

The aim of the study is to present a methodology of analyzing pollution emissions in a medium-sized city using modern traffic simulations in the aspect of minimizing exhaust emissions. The transport in the city of Czestochowa (Poland), despite well-developed public transport, mainly relies on the use of passenger cars in urban traffic. Therefore, in order to improve urban traffic conditions and minimize the risk of the occurrence of

transportation problems as well as reduce exhaust emissions in the city, it is necessary to properly develop the major arteries of the city of Czestochowa in terms of infrastructure, in particular the most important intersections as their proper functioning will ensure the right volume of traffic, which will impact the road conditions in the whole city. Traffic in the city is controlled by means of road signs and traffic lights.

The simulation of traffic on the arteries of the city of Czestochowa focused on data from a sequence of intersections on Armii Krajowej Avenue, which generate heavy traffic and play an important role in the urban traffic capacity. They constitute important connections to the road traffic generated by the nearby national road E1 and the approach to the city's newly built beltway. The largest of the intersections analyzed, the intersection of Jana Pawła II Avenue and Armii Krajowej Avenue, is the main spot where traffic coming from these streets is eased, and it comprises the main roads leading to the city center as well as in the opposite direction, out of the city. It has a huge traffic volume, which is eased at the next analyzed intersection of Armii Krajowej Avenue and Dekabrystów Street and further at the intersection with Kisielewskiego Street, constituting access to some of the largest residential districts of the city as well as numerous workplaces, educational and commercial facilities.

Similar transportation arrangements with analogous traffic volume characteristics can be found in many Polish cities. Therefore, both the analysis method and the way of assessing the impact of traffic organization improvements on pollution emissions can be easily applied to other cities.

4. Methodological Assumptions for the Study

The main research hypothesis of the experiment can be defined as follows: through improvements in traffic organization and communication infrastructure, we increase both the capacity and smoothness of vehicle passage with a significant reduction in emissions, while respecting the above-mentioned technical and economic limitations. In global terms, achieving these goals will improve environmental ecology and the efficiency of public transport.

Methodologically, this research study required:

- acquisition of real traffic data. In order to carry out the simulation, the traffic measurement and traffic light cycles at each intersection of the main artery at selected times had to be collected,
- definition of the simulation model and its parameterization, notably setting the correct initial values, establishing the right guidelines for the simulation in order to perform the simulation process adequate to the reality,
- analysis of traffic intensity on the selected intersections,
- presentation of proposed improvements, modification of the model and initial validation of the solutions.

The measurement of traffic volume in the aspect of minimizing exhaust emissions was performed for a sequence of intersections located at a section of Armii Krajowej Avenue in Czestochowa (Figure 1) referred to further in the paper as an artery. The artery under study comprises the intersection of Armii Krajowej Avenue and John Paul II Avenue, the intersection of Armii Krajowej Avenue and Dekabrystów Street, in addition to the intersection of Armii Krajowej Avenue and Wyzwolenia Avenue, marked in the figure as A, B and C respectively.

The total distance of the artery under analysis is 1.9 km. This distance consists of a 900-meter distance between the intersection of Armii Krajowej Avenue and Jana Pawła II Avenue (A) and the intersection of Armii Krajowej Avenue and Dekabrystów Street (B), as well as a 1-km distance between intersection B and the intersection of Armii Krajowej Avenue and Wyzwolenia Avenue (C). The travel time at the maximum permitted speed (50 km/h) and with functioning traffic lights will take 4 min. Observations showed that the actual travel time was 3 min longer. Thus, any shortening of such time would be translated into measurable environmental benefits and economic effects.

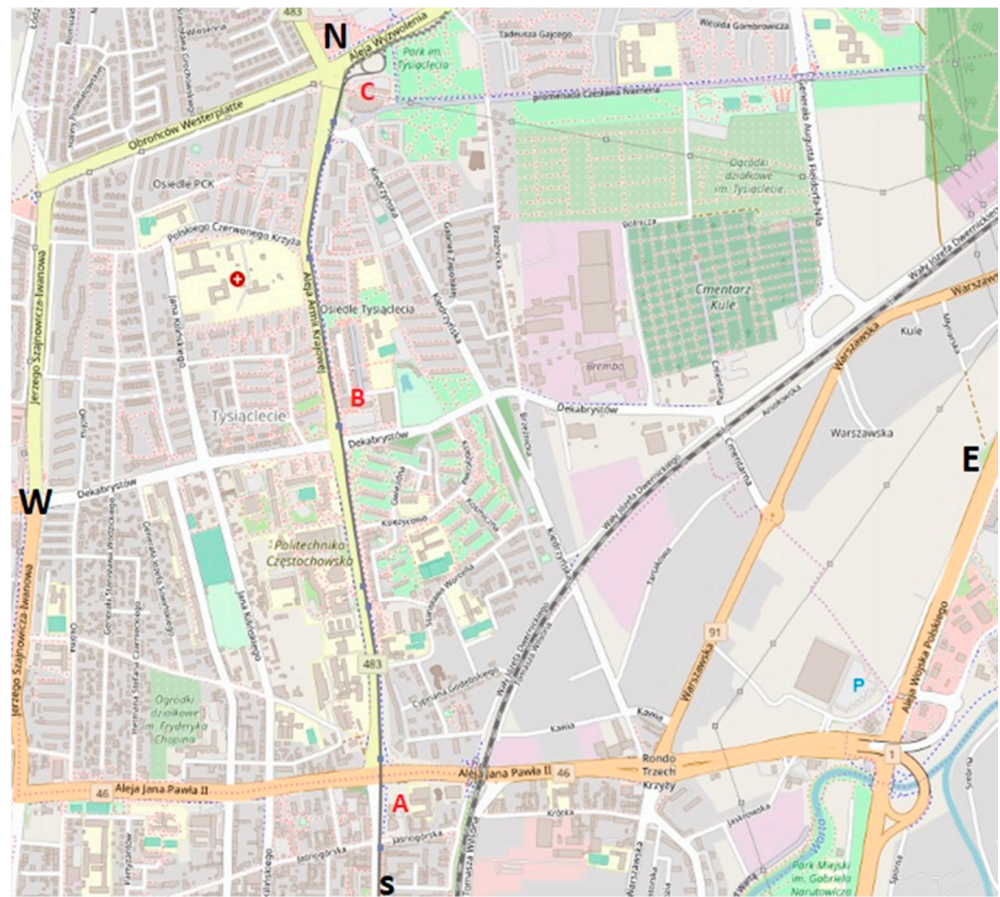


Figure 1. Map of area covered by the study.

Following the assumptions of the study, the traffic volume and the operation cycle of the traffic lights were measured at the pre-selected intersections. The measurements were performed on week days, chosen randomly, during rush hours in the city between 4.00 PM and 5.00 PM. The traffic volume generated during that period was significantly higher in relation to other periods. The selection of rush hours for the study enabled observation and analysis of errors in urban traffic organization as well as related transportation problems of the city, including pollution emission. The measurement was performed by counting vehicles: passenger cars, lorries and public transport vehicles comprising trams and buses driving through the intersections.

5. Measurement Results

The measurement results presented in tables constitute the actual values obtained through observation of the traffic intensity and vehicles travelling through the intersections on the artery.

In order to obtain clear and reliable results, the study was conducted in accordance with the geographical directions, and the results are presented in Table 1, where they are divided for each intersection into entering and exiting vehicles from the north, south, east or west.

Both the observations and conducted analysis confirm the hypothesis formulated in the paper that the intersection of Jana Pawła II Avenue and Armii Krajowej Avenue generates the highest volume of traffic, and consequently the most exhaust, mainly in the directions of city entry and exit (E-W). The intersection of Armii Krajowej Avenue (N-S) and Dekabrystów Street as well as the intersection of Armii Krajowej Avenue and Wyzwolenia Avenue generate much less traffic volume. Armii Krajowej Avenue, as one

of the city's major roads, allows inhabitants to reach multiple workplaces and the most populated residential districts.

Table 1. Traffic statistics for selected intersections of the artery.

Intersection	Direction	Passenger Cars	Lorries	Buses	Trams
Jana Pawła II Avenue (JPII) and Armii Krajowej Avenue(AK)					
Armii Krajowej Avenue and Jana Pawła II Avenue (entry)	N	184	2	0	3
	E	364	7	1	0
	S	159	0	4	3
	W	437	7	0	0
Armii Krajowej Avenue and Jana Pawła II Avenue (exit)	N	176	0	2	3
	E	450	7	0	0
	S	160	0	2	3
	W	341	6	1	0
Armii Krajowej Avenue and Dekabrystów Street					
Armii Krajowej Avenue and Dekabrystów Street (entry)	N	141	0	0	3
	E	184	0	2	0
	S	198	0	0	3
	W	172	1	1	0
Armii Krajowej Avenue and Dekabrystów Street (exit)	N	118	1	0	3
	E	159	0	1	0
	S	161	0	0	3
	W	193	0	1	0
Aleja Armii Krajowej Avenue and Aleja Wyzwolenia Avenue and Kisielewski Street					
Armii Krajowej Avenue and Kisielewskiego Street and Aleja Wyzwolenia Avenue (entry)	N	138	3	1	3
	E	234	1	2	0
	S	306	1	4	3
	W	185	0	0	0
Armii Krajowej Avenue and Kisielewskiego Street and Wyzwolenia Avenue (exit)	N	193	2	1	3
	E	232	0	2	0
	S	207	2	2	3
	W	200	1	0	0

It should be borne in mind that the results of the study are affected by numerous factors such as the time of day, type of workday, unpredictability of road or weather conditions as well as the methods employed to study traffic volume. These factors may significantly decrease or increase the obtained numbers when conducting the measurements.

The traffic light cycle is important information in traffic simulation and analysis. To illustrate the light cycles on the artery intersections, the following measurements, extracted from the report, are given below.

Jana Pawła II Avenue and Armii Krajowej Avenue:

- (1) From the direction of Armii Krajowej Avenue, direction N-S:
 - turn lane into Jana Pawła II Avenue, eastern direction: green light: 18 s, red light: 86 s,
 - lane for driving straight ahead, southern direction: green light: 85 s, red light: 23 s,
 - turn lane western direction: red light: 67 s, green light: 42 s.

- (2) From the direction of Armii Krajowej Avenue, direction S-N:
- lane for driving straight ahead north and right turn lane to the east. Green light: 85 s, red light: 23 s,
 - left side westbound lane. Green light: 85 s, red light: 23 s.
- (3) From the direction of Jana Pawła II Avenue, direction E-W:
- lanes for driving straight ahead west and turn to the north. Green light: 70 s, red light: 37 s,
 - lane for turning to the south. Green light: 95 s, red light: 13 s.
- (4) From the direction of Jana Pawła II Avenue, direction W-E:
- lanes for driving straight ahead to the east. Green light: 75 s, red light: 35 s;
 - left side northbound lane. Green light: 95 s, red light: 15 s.

Similar data were collected at the intersections of Armii Krajowej Avenue with the intersections with Dekabrystów Street and Wyzwolenia Avenue. Table 2 contains the results of the observations conducted three times for three chosen days counting the number of vehicles passing through during one green light phase on the artery Armii Krajowej-through the three analyzed intersections. The data are related to the north and south directions-vehicles travelling straight ahead through the whole artery of intersections on Armii Krajowej Avenue and vehicles turning at the intersections of Armii Krajowej Avenue to the west and east.

Table 2. Results of observations.

Intersection	Direction	Thursday			Friday			Saturday		
Vehicles driving during one light phase Armii Krajowej Avenue N-S and S-N At intersection with Aleja Jana Pawła II Avenue										
Armii Krajowej Avenue and Jana Pawła II Avenue (entry)	Straight ahead S	21	14	16	25	18	20	18	9	11
	Left E	17	20	19	21	24	22	13	15	16
	Right W	4	3	1	10	8	6	1	3	0
Armii Krajowej Avenue and Jana Pawła II Avenue (exit)	Straight ahead S	12	10	16	16	14	20	13	15	11
	Left E	5	0	3	10	8	9	2	4	3
	Right W	1	4	2	5	9	7	2	1	0
Vehicles driving during one light phase Armii Krajowej Avenue N-S and S-N At intersection with Dekabrystów Street										
Armii Krajowej Avenue and Dekabrystów Street (exit) N-S	Straight ahead S	10	8	12	15	12	18	7	5	10
	Left E	0	4	2	4	8	6	3	2	0
	Right W	4	3	5	8	5	9	2	3	4
Armii Krajowej Avenue and Dekabrystów Street (exit) S-N	Straight ahead S	16	24	21	20	27	25	13	20	16
	Left E	1	3	3	6	5	8	4	1	3
	Right W	0	2	1	4	3	6	2	0	4
Vehicles driving during one light phase Armii Krajowej Avenue N-S and S-N At intersection with Wyzwolenia Avenue										
Armii Krajowej Avenue and Wyzwolenia Avenue (exit) N-S	Straight ahead S	9	16	7	14	21	12	13	6	6
	Left E	0	0	4	5	3	7	2	4	3
	Right W	2	4	5	6	3	8	0	3	3
Armii Krajowej Avenue and Wyzwolenia Avenue (exit) S-N	Straight ahead S	12	16	12	15	20	14	9	12	10
	Left E	2	1	3	6	5	7	0	2	1
	Right W	3	2	4	7	6	8	3	0	1

Analysis of the traffic at each of the intersections shows that the traffic lights at the intersection of Armii Krajowej Avenue and Jana Pawła II Avenue indicated that only slight modification of the parameters is required. The green light phases were extended for vehicles driving E-W and W-E, where the highest traffic volume was observed. An additional advantage was achieved by the non-collision turn lanes, which follow a different traffic light cycle than the one applying to straight ahead movement. They ensured continuous traffic flow without vehicles being blocked at the intersection. A similar situation was at the intersection of Armii Krajowej Avenue and Dekabrystów Street. Thanks to the non-collision turn lanes, vehicles were not blocked at the intersection when driving in one green light phase. The next intersection with Wyzwolenia Avenue did not need such a solution. The objectives of the simulation were achieved. In the next section it will be shown that the flow of traffic by reducing the travel time was improved as well as fuel costs, emissions, and the number of stops.

6. Traffic Simulation Reports

The latest SUMO microscopic vehicular pollutant emission model for optimizing traffic in order to reduce its environmental impact was published by Krajzewicz [40]. Because of the specificity of our case study, the applied approach was slightly modified. First, a section of the main artery was extracted from the OpenStreetMaps, database, along with nearby roads responsible for generating the traffic volume in the simulation. The traffic flow in a SUMO simulation takes place microscopically, generating traffic volume on the road infrastructure section under analysis.

The simulations were performed assuming gasoline and diesel passenger vehicles (Euro norms 4 to 6). There were no vehicles belonging to V2X or V2V in the simulation. The following vehicle and simulation parameters were taken:

- dt (time step): 1 s
- v_{begin} (initial velocity): 13.89 m/s (~50 km/h)
- v_{max} (maximum velocity): 13.89 m/s (~50 km/h)
- a_{max} (maximum acceleration): 1.0 m/s²
- d_{max} (maximum deceleration): −4.5 m/s²

The simulated traffic light has a cycle duration of 60 s, with a green time that starts at second 0 and ends after 25 s. It is followed by a yellow phase of a 3 s duration. Thereby, the last phase (red) has a duration of 32 s.

Concerning vehicle movement, a simple kinematic method was considered; it means that the acceleration or decelerations were constant.

The values used in the simulation were as follows:

- Delay control value–*Delay*: 200 ms;
- Duration of the simulation–*Time*: 1 h;
- Scaling of vehicle traffic volume–*Scale Traffic* for hours 10:00–11:00 a.m. 4:00–5:00 p.m. value 9.

Table 3 presents the results of the simulation. The values obtained as a result of traffic volume simulation are as follows:

- *Simulation time*: 3600 s (1 h),
- *Duration of green lights*: the default value is 90 s,
- *Number of vehicles*: including inserted: 2977, running: 1836, waiting: 120.
- *Duration-the time needed by a vehicle to travel the route*: 563.50 s,
- *WaitingTime*-time when a vehicle's speed was below 0.1 m/s: 337.29 s,
- *TimeLoss*-the time lost due to traffic slow down at the intersections: 428.35 s.

The generated reports show a significant increase in the value of the average travel time, the average forced stop time or the average time lost due to driving slower than allowed.

For example, at the intersection of Armii Krajowej Avenue with Wyzwolenia Avenue, the formation of a traffic jam is the result, among other factors, of not adapting the length of green light to increased traffic intensity and the lack of an additional lane for left and

right turns. Based on the traffic peak hours, the simulation of the emission characteristics was estimated in the simulation. The main parameters for the operation conditions are: engine speed, engine power as well as the temperature of the engine and the exhaust aftertreatment systems. Second, the following driving states have to be examined: (a) Cruising (at a constant speed), (b) Acceleration, (c) Deceleration, and (d) Stop time. Stop times with engine idling should be minimized, for example by turning the engine off during stand still as done automatically by the Stop/Start systems of modern engines or by prolonging the deceleration time with the engine in the “fuel cut-off” mode. Though, the choice of the speed and acceleration has an effect on a vehicle’s emissions even if staying in the same driving state. To determine optimal accelerations and velocities for each of these states, simulations using the instantaneous emission model were performed.

Table 3. Reports on traffic volume simulations.

Simulation ended at time: 2000.00 Reason: The final simulation step has been reached. Performance: Duration: 727421ns Real time factor: 2.74944 UPS: 1727.410949 Vehicles: Inserted: 1367 (Loaded: 1377) Running: 503 Waiting: 10 Teleports: 178 (Jan: 103, Yield: 54, Wrong Lane: 21) Statistics (avg): RouteLength: 1980.31 Duration: 461.49 WaitingTime: 246.10 TimeLoss: 319.44 DepartDelay: 9.38	Simulation ended at time: 2000.00 Reason: The final simulation step has been reached. Performance: Duration: 475650ms Real time factor: 4.20477 UPS: 7856.076947 Vehicles: Inserted: 2977 (loaded: 3097) Running: 1836 Waiting: 120 Teleports: 644 (Jam: 445, Yield: 151, wrong lane: 48) Statistics (avg): RouteLength: 1821.80 Duration: 563.50 WaitingTime: 337.29 TimeLoss: 428.35 DepartDelay: 17.28
Hours of traffic 10:00–11:00	Hours of traffic 16:00–17:00

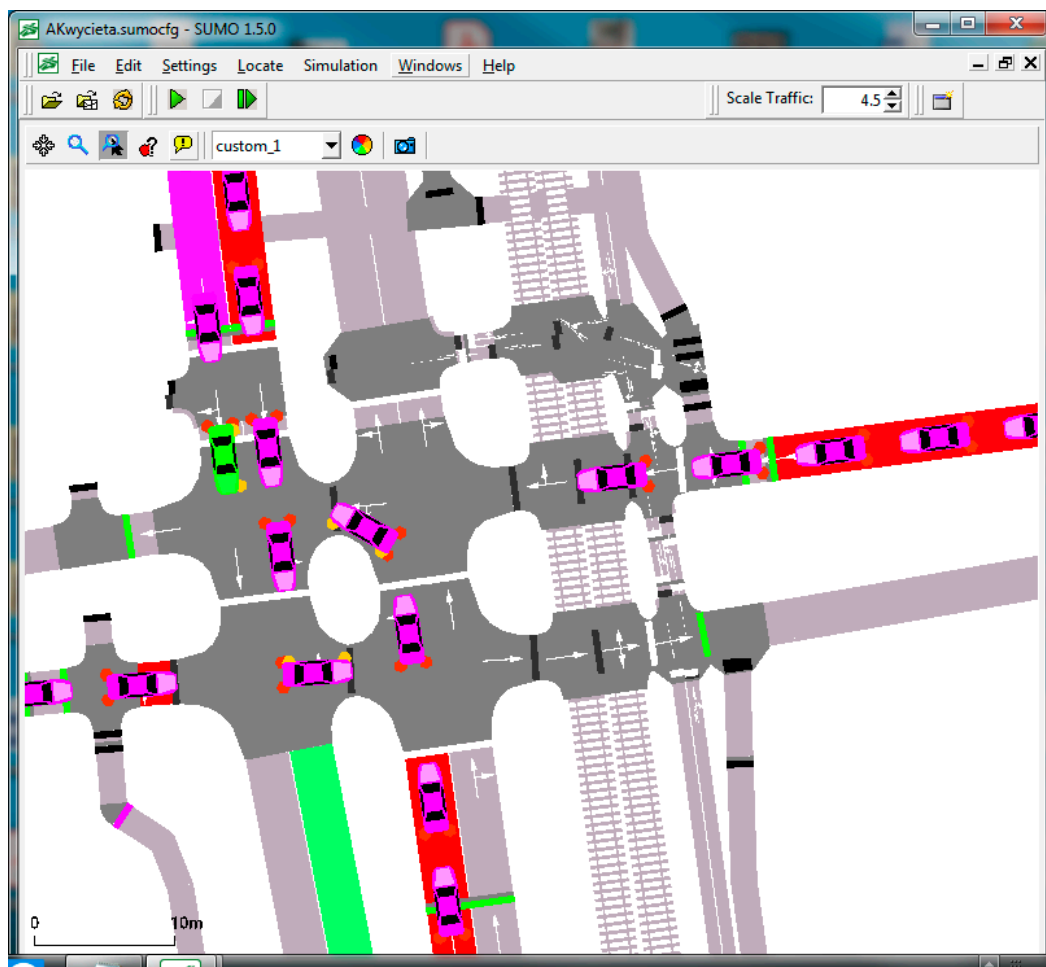
Before performing the simulation, appropriate parameters were assumed in accordance with earlier-conducted studies in the context of traffic volume in the aspect of exhaust emissions for the whole sequence of intersections on Armii Krajowej Avenue. With a change in the time of day from 10:00–11:00 AM to 4:00–5:00 PM, the traffic gradually increased resulting in a higher traffic volume and thus a reduced capacity. The reports from the simulation show that the formulated hypothesis was confirmed. The generated report (Table 4) indicates higher values for the average travel duration, average waiting time and average time lost due to a driving pace slower than the speed limit. The performed simulation sufficiently reflects the planned scenario representing the traffic volume situation generated in the study.

The SUMO software can generate an exhaust emissions report, which, based on the simulations, shows visual data on fuel consumption, emissions of CO, CO₂, nitrogen compounds, hydrocarbons and fine particle substances. The simulations allowed the average levels of the above-mentioned emissions and fuel consumption to be determined for each generated vehicle. The analyst can observe the traffic-related air pollution measurements during the simulation. In Figure 2, the different colors illustrate various levels of CO₂ pollution by lane and vehicle, according to predefined thresholds.

Traffic simulations in SUMO generate data on the average level of emitted pollutants such as: carbon monoxide (CO), hydrocarbons (HC) that constitute a group of chemical compounds, which combined with UV radiation create the so-called smog. All results of the simulations are not presented in the article due to the large amount of data. Table 4 presents a fragment of the pollution emissions report during the defined traffic hours for the individual lanes of the artery, where each lane is identified by ID edge. This data can be used to conduct a more detailed analysis of the impact of traffic organization changes, not only on specific sections of the artery, but also the whole artery or in the city area.

Table 4. Report on analysis of emission on lanes of the artery.

A	B	C	D	E	F	G	H	O	P	Q	R	S
ID edge	sam- pledS	CO_abs	CO2_abs	HC_abs	PMc_abs	Nox_abs	FLUE- abs	CO_perVeh	CO2_perVeh	HC_perVeh	PMx_perVeh	NOx_perVeh
144900310#0	46	2833	15,5798	17	3	65	67	6	316	0	0	0
-141900310#0	50	1904	10,7433	11	2	45	46	4	234	0	0	0
141900310#1	82	6519	30,7483	37	6	129	132	35	16S0	0	0	1
-141900310#1	81	3839	18,4152	22	3	77	79	22	1074	0	0	0
141900310#2	233	1,4157	94,0635	87	18	391	404	145	9665	1	0	4
-141900310#2	259	9368	57,3354	56	10	234	246	103	6314	1	0	3
141900311#0	1314	8,0113	275,4512	429	54	1156	1184	622	2,1399	3	0	9
-141900311#0	701	4,3924	257,3766	261	48	1071	1106	408	2,3888	2	0	10
216136706	857	3,7461	261,1906	232	46	1058	1123	478	3,3321	3	1	14
-216136706	1096	3,9710	279,65S9	246	47	1120	1202	434	3,0536	3	1	12
216136709#0	106	1,3771	38,4004	72	9	170	165	231	6451	1	0	3
216152047#0	1931	12,1843	376,7440	643	75	1599	1620	974	3,0124	5	1	13
216152047#2	196	1,3141	55,4099	73	11	235	238	104	4383	1	0	2
-216152047#2	394	2,6324	83,8569	140	17	359	360	141	4497	1	0	2
216152050#1	1564	21,6916	386,9604	1079	93	1752	1663	1503	2,6811	7	1	12
216152051#1	117	1,2572	31,8221	65	7	138	137	31	777	0	0	0
216152051#2	420	6,0334	108,2279	300	26	489	465	179	3206	1	0	1

**Figure 2.** Visualization of pollution emissions.

It should be noted that the simulation results only indicated potential directions for improving traffic flow. The model adopted in the simulator has a number of restrictions,

such as the lack of the ability to take into consideration all vehicle classes, the lack of vehicle breakdowns and accidents, widespread compliance with road traffic rules by drivers, a uniform way of driving vehicles. For these reasons, the simulation results can be treated as an optimistic representation of the existing or future road situation.

7. Proposals Concerning Improvements and Changes in Traffic Organization

7.1. Building an Additional Lane

At the intersection of Armii Krajowej Avenue, Wyzwolenia Avenue, Obrońców Westerplatte Street and Kisielewskiego Street, when driving on Kisielewskiego Street towards the Hala Polonia building, there are two lanes available (Figure 3). One lane is for driving straight ahead, the other is for driving straight ahead and turning left. In a situation of higher traffic volume, a driver turning left will slow down the vehicles behind him/her wishing to continue driving straight ahead. Building a third lane that only turns left would significantly improve driving through this intersection.

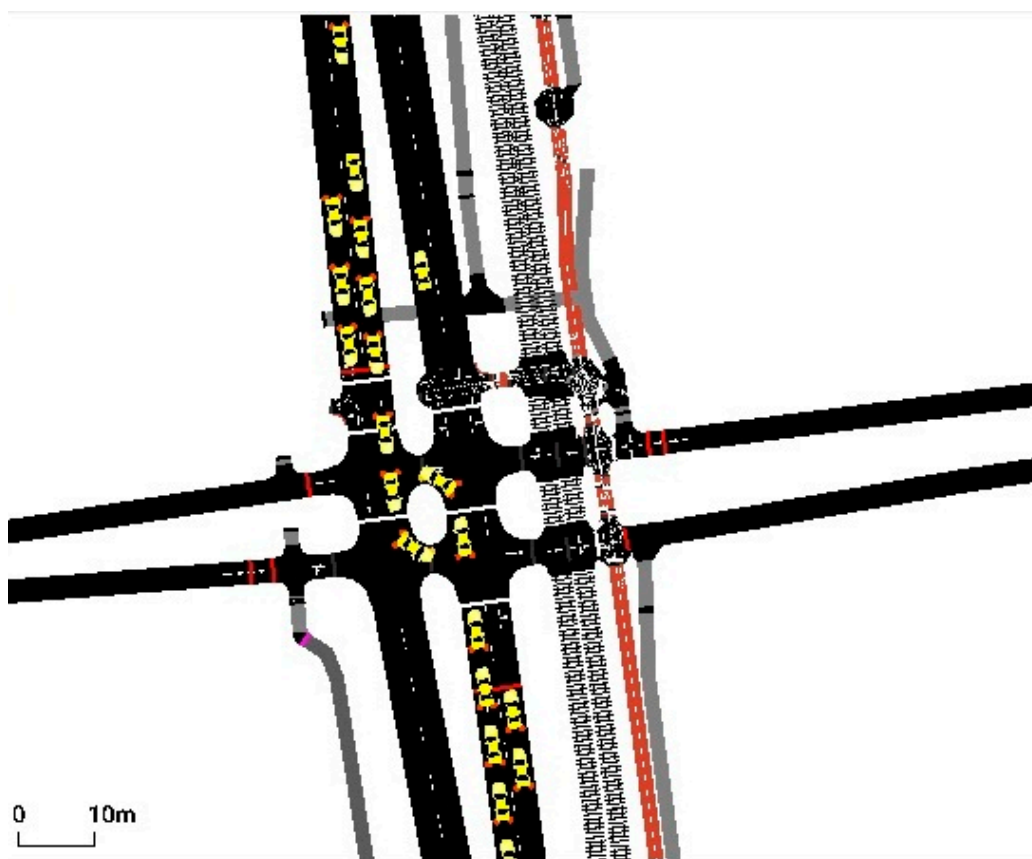


Figure 3. View of intersection before implementation of improvements.

Prior to improvements, the generated section contains only one lane, which allows vehicles to drive straight ahead and to make a turn. This reduces the traffic capacity. An additional turn lane would relieve the lane for driving straight ahead.

Building an additional lane designed only for turning relieved the lane for driving straight ahead, which previously was also used for turning, and thus had a lower traffic capacity.

7.2. Extended Turn Lanes

At the intersection of national road 46 and voivodeship road 483 from the direction of Trzech Krzyży roundabout, there are often traffic jams due to the exit from national road 1 located nearby. The traffic jam that forms when the light is red is often so long

that the vehicles that wish to turn left are unable to enter the lane designed for this maneuver because they are blocked by the vehicles heading straight ahead (Figure 4). Lengthening the left-turn lane would make it much easier to change a lane and perform the desired maneuver.

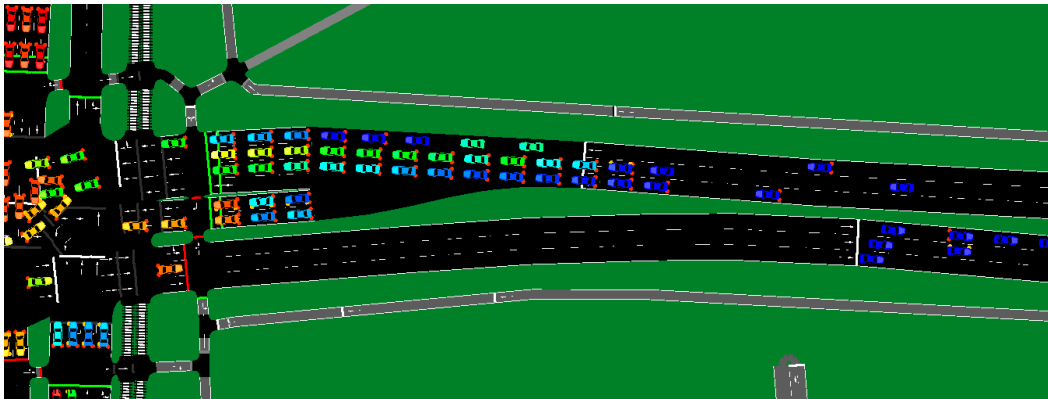


Figure 4. Situation at intersection after implementation of improvements.

Upon implementation of improvements 2 and 3 in the model of the roads (Table 5), SUMO software was used to perform a traffic simulation with the values assumed for traffic rush hours between 4:00 and 5:00 PM.

Table 5. Generated simulation report after implementation of improvements 2 and 3.

Simulation ended at time: 2000.00
Reason: The final simulation step has been reached.
Performance:
Duration: 41,9054ms
Real time factor: 4.77265
UPS: 9673.323724
Vehicles:
Inserted: 3045 (Loaded: 3142)
Running: 2069
Waiting: 97
Teleports: 666 (Jam: 447, Yield: 179, WrongLane: 40)
Statistics (avg):
RouteLength: 1776.65
Duration: 561.26
WaitingTime: 342.05
Timeloss: 427.79
DepartDelay: 31.79

7.3. ITS

Intelligent Transportation Systems (ITS) combine various technologies that provide innovative services connected with transport and traffic management in a city. Currently, the city of Czestochowa does not have an ITS due to the high cost of its license. However, the implementation of ITS would increase the safety of road traffic participants, improve the mobility of passengers and goods, as well as reduce pollution of the environment. A profit and loss analysis should be performed to justify the purchase of such a system. It is worth mentioning that ITS is the best solution in situations when emergency vehicles and public transport vehicles are present in traffic. The technologies used by the system allow it to recognize such vehicles and automatically change the traffic lights. Thanks to such synchronization, the vehicle can drive through a few intersections without stopping. The so-called “green wave” enables emergency vehicles to arrive at the incident site faster, whereas public transport-to run according to the timetable.

7.4. Information about Traffic Organization at the Next Intersection

Driving through the intersection of Armii Krajowej Avenue and Jana Pawła II Avenue from the direction of national road 1, a vehicle that wishes to turn left can use two lanes. However, if the vehicle has driven through the intersection on the leftmost lane and stayed on it, the vehicle's driver is forced to make another left turn at the next intersection. A vehicle at the analyzed intersection that wishes to turn left and drive straight ahead through the next intersection is forced to change the lane right after leaving the intersection, thus creating a risk of collision and putting other participants of the traffic at risk. A similar situation is at the intersection of Armii Krajowej Avenue and Dekabrystów Street: when driving in the left lane straight ahead from the direction of Kilińskiego Street, a driver is forced to turn left at the next intersection. One of the solutions to this problem is to put a sign before the entry into the intersection to warn drivers of what they can expect in a moment. As a result, drivers would be informed that if they continued driving in the same lane, they would be forced to exit the main road, i.e., divert from their route.

7.5. Countdown Timers on Traffic Lights

Countdown timers, which indicate how much time is left before the lights change, are a very convenient solution. However, many intersections lack this feature, which is designed to increase safety of both drivers and pedestrians. In Czestochowa, of the intersections at Armii Krajowej Avenue, only drivers driving through the intersection of Dekabrystów Street with Armii Krajowej Avenue can benefit from this feature. Installing countdown timers at the intersection of Aleja Armii Krajowej Avenue, Wyzwolenia Avenue, Obrońców Westerplatte Street and Kisielewskiego Street as well as at the intersection of Armii Krajowej Avenue and Jana Pawła II Avenue would contribute to increased safety and reduced risk of collision. Moreover, the timer displays should be modernized. The number showing how many seconds are left before the lights change is clearly visible to the driver only when his/her distance from the traffic lights is 40 m or less. The timer should be larger in size so that it can be more visible from a greater distance. Additionally, apart from countdown timers there should be a light flashing continuously from 5 s until the change of lights, which would inform drivers whose distance from the traffic lights makes it impossible to clearly see the number on the display. Knowing that the lights would change in a moment, they could slow down and minimize the risk of driving through a red light. These improvements related to countdown timers indicating how much time is left before the lights change would undoubtedly contribute to greater safety of pedestrians and vehicles, as well as reduce the risk of collision.

7.6. Summary of the Proposed Improvements

By analyzing and identifying traffic problems in cities, it is possible to minimize them by implementing improvements aimed at enhancing traffic flow, which brings numerous environmental and economic benefits such as a reduced travel time and reduced number of stops, resulting in lower costs of fuel consumption and pollution emissions.

The most cost-effective of the proposed solutions seems to be ITS. The implementation of ITS requires by far the most financial resources, but brings a wide range of benefits. The cost of implementing ITS in a medium-sized city of less than 200 sq. km exceeds 10 million PLN. Extending a lane and building a new traffic lane would require a much smaller financial outlay. The investment is expensive, but not as much as the previous proposal. Installing countdown timers on traffic lights costs, depending on the intersection, from 10,000 PLN per intersection. Despite the relatively high costs of implementing ITS, it brings a range of important benefits in terms of improving a city's traffic. ITS enables, among other things, a reduction in travel time on the artery, a decrease in fuel consumption costs, a cut in emissions, a reduction in the number of stops, a curtailment of traffic delays and a lowering of accident rates. The effectiveness of the potential results of implementing ITS offsets the costs of its implementation.

Countdown timers on traffic lights are an important proposal to improve traffic at the analyzed intersections. Undoubtedly, they contribute to increased safety of road traffic participants and efficient movement through an intersection. Countdown timers on traffic lights offer several benefits such as a reduction in the number of collisions, an increased traffic capacity and the elimination of unnecessary delays, fewer drivers going through intersections on a red light, improved fuel efficiency as a result of smoother driving, and consequently less wear and tear of a vehicle, lower fuel consumption in addition to lower exhaust and noise emissions.

8. Conclusions

The presented methodology it is an initial stage, an research prompting a broader one for analyzing the level of pollutant emissions is in particular oriented to solving communication problems of medium-sized cities in which several thoroughfares are decisive for communication and environmental ecology. The advantages of this approach are also low research costs, which do not require large investment outlays or costly expertise.

The SUMO simulator turned out to be a useful tool that allows one to quickly assess and check the functioning of changes introduced into the infrastructure. Thanks to the microscopic models used in the simulations, it was possible to obtain estimated data on the behavior of individual vehicles, CO₂ emissions, fuel consumption and information on the traffic capacity of the analyzed area.

By using state-of-the-art traffic simulation and management software, medium-sized city managers such as those presented in the study can better understand the current transport situation and take action in the context of sustainable urban development.

The presented research for a medium-sized city in Poland, i.e., Częstochowa, allows to show the infrastructure situation and the possibility of introducing new solutions to improve the ecological situation in many similar cities. Advanced simulation that realistically depicts traffic conditions and infrastructure in a digital replica of the respective city aims at three aspects: providing a virtual representation of the status quo of traffic, including detailed calculations of CO₂, NO_x and PM₁₀ emissions, identifying and assessing best practices before implementing measures in the field and analysing environmental factors and how they impact traffic flow and capacity. The positive results and experience presented in many areas allow the continuation of research and analyzes into the ecological aspects of communication solutions. They will allow a further increase in the efficiency of the transport system, improving the protection of life and health of road users and the quality of the natural environment.

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