Optimization of the Urban Highway Acceleration Lane Length Using Traffic Simulations

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Abstract

Design recommendations for the acceleration lane length are based on research and monitoring data made decades ago and have recently been the subject of discussions and innovations. Designing a highway acceleration lane differs between urban and non-urban areas by a large number of parameters. Specificities of an urban space, multimodal demands of traffic users, environmental requirements and inherited spatial relationships make optimization of the acceleration lane length a real challenge. The development of analytical, analytical-empirical and simulation methods for evaluating design solutions is generated by the desire to make the analyses performed in the planning phase as realistic as possible. Microsimulation traffic tools, such as VISSIM, enable the analysis of variant solutions and the optimization of road design elements for existing as well as for future traffic demands. This paper presents an analysis of two existing acceleration lanes on the southern bypass of the city of Osijek. Microsimulation results show that there is a potential for shortening the length of acceleration lanes in the current traffic demand conditions. Various scenarios of the increase in traffic of the main and secondary traffic flows have been analysed. The results were evaluated through the criteria of selected functional indicators, which are average delays and queue lengths. This research contributes to the methodology of applying modern simulation tools in the analysis and optimization of traffic infrastructure elements in local conditions.

Keywords: acceleration lane length, VISSIM, urban highway, Case Study

1. Introduction

The acceleration lane length is adopted based on project recommendations [1, 2, 13, 16]. The complexity of the merging of traffic flows requires proper geometric design [2, 13] that must allow for safe and undisturbed interweaving of secondary and main traffic flows. Due to increased traffic demand, changed traffic flow structure, the relevant vehicle performance, possibility of introducing intelligent transport system (ITS) technologies into the transport system, increasing the efficiency and safety of the inflow manoeuvre, the acceleration lane length is the subject of new research and numerous case studies in real traffic conditions [1, 3, 8, 10, 11, 21, 22].

Simulation models are used to optimize elements of the transport infrastructure that cannot be performed on a real system for functional and safety reasons [3, 15, 23]. Different types of models are intended for different traffic analyses [6], and microsimulations are most commonly used to optimize elements of the transport infrastructure.

Because of the scope of the conducted research, the aim of this paper is not to question the design recommendations, but to analyse the results obtained by applying modern simulation methods to observed elements of the transport infrastructure in local conditions.

Functional indicators of acceleration lanes of urban highway were analysed using the VISSIM microsimulation model. Two acceleration lanes on the southern bypass of the city of Osijek were selected for the case study. Acceleration lanes were selected at the intersections of Čepinska and Trpimirova, because of the highest rate of the average annual daily traffic (AADT) on the entire urban highway, according to official counters of Hrvatske ceste dd as the responsible legal entity.

2. Background

Acceleration lane is a speed change area or lane containing added pavement at the edge of through traffic lanes to allow vehicles to accelerate before merging with the main traffic flow. The basic elements shown in Figure 1 distinguish between the total (La) and effective or available acceleration lane length (Lg).

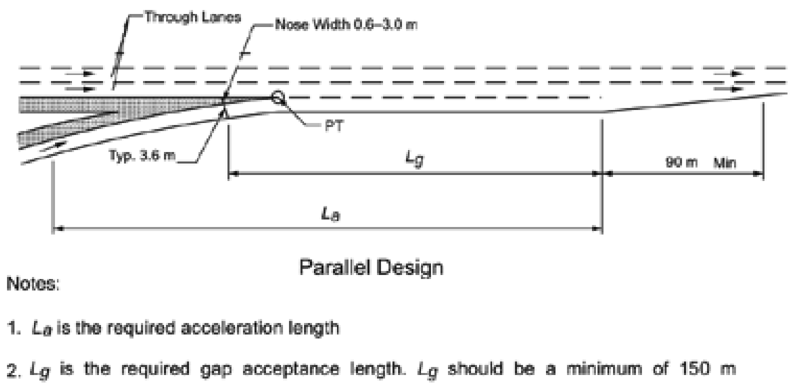

Figure 1: Acceleration lane
Source: [2]

Acceleration lane length is adopted based on design recommendations [2, 13, 16]. The rapid development of the automotive industry and the introduction of new transport technologies require analysis and innovation of existing design recommendations in line with new traffic requirements [1, 3, 8, 10]. Recommended acceleration lane lengths have not been updated since the 1950s. The project recommendations do not specifically address the lengths required to accelerate trucks, and research shows that the required acceleration lengths for medium and heavy trucks are approximately 1.3 and 1.6 times the Green Book design guideline, respectively [21].

The available acceleration lane length affects the behaviour of drivers in acceleration and flowing into the main traffic flow manoeuvres [22]. For ramps with a long acceleration length, drivers tend to accelerate at a lower and more comfortable rate than they do at ramps that have a shorter acceleration length [22]. New traffic requirements generate the need to make better use of the existing transport infrastructure through the introduction of ITS technologies in traffic regulation. One way to increase the efficiency and safety of merging operation is to use traffic lights - ramp metering is the use of traffic signals at highways on ramps to control the rate of vehicles entering the highway. The signals can be set for different metering rates to optimize highway flow and minimize congestion. Signal timing algorithms (red-green phase) are determined based on real time data obtained by detecting the time gaps of the main traffic flow [20]. Thereby it is important to note that the effective acceleration length in this case is the length between the stop line and the merge point. The sight distance directly influences the usability of the length of the acceleration lane (Lg, Figure 1). The location where vehicles stop (stop line location) should have adequate sight distance to the highway traffic flow to assist a safe and efficient merge.

An analysis of the impact of a particular segment of transport infrastructure on a broader segment of the transport system should be made in the planning phase, regardless of whether it is the construction and reconstruction of traffic objects and/or changes in the traffic regulation. The development of mathematical, mathematical-empirical and simulation models of the transport system is generated by the need to make the analysis of the impact of the planned infrastructure facilities and traffic-regulatory measures as realistic as possible. Simulation traffic models have the challenging task of modelling a complex stochastic system, such as a traffic system. In addition to the physical part of the system that relates to the geometric characteristics of the infrastructure and which can be mathematically described, it is also necessary to simulate its operationalization, traffic flow [7, 11, 23], which is influenced by variable human behaviour [3, 4, 9, 11, 17]. The application of different simulation models must be considered in the context of temporal and spatial reach, as they have been developed for specific types of traffic analyses and are intended for making different decisions [4, 5, 6].

Microsimulation traffic models are the most commonly used tools in optimizing transport infrastructure elements [23] and are also used to optimize traffic supply and demand [9], optimize traffic flow [7, 11, 15], compare variant solutions [14] for the short or medium-term planning, and to analyse functional and safety characteristics of intersections [12, 17, 18, 19]. The VISSIM microsimulation model was used to analyse the acceleration lane length under local conditions. VISSIM is a stochastic (not completely determined by the results of the previous modelling phase), discrete (time-oriented), and microsimulation (models each entity) traffic model, that began to develop in the early 1970s in Germany, at the Karlsruhe University.

3. Case Study

3.1 Selected entering ramps

The southern bypass of the city of Osijek was chosen as the location for the case study and acceleration lanes were observed at the intersections of Čepinska and Trpimirova, due to the highest AADT, in accordance with the results of the analysis. The intersections of Čepinska (Figure 2a) and Trpimirova (Figure 2b) are in the shape of a four-leaf clover. The horizontal-plan elements were selected according to a calculating speed of 30 km/h, and total lengths of effective acceleration and deceleration lanes (Lg, Figure 1) were constructed over a length of 250 meters.

a) (b)

Figure 2: Intersections of Čepinska (a) and Trpimirova (b)
Source: [24]

3.2 Existing traffic loads and speeds

Manual traffic counting and traffic recording were carried out at the locations of the Čepinska intersection (Tuesday, 8th May, 2018) and the Trpimirova intersection (Wednesday, 9th May, 2018). Traffic was counted twice a day, between 6.30 and 8.30 a.m. and between 2.30 and 4.30 p.m. on the main traffic lanes (the main lane and the overtaking lane) and on acceleration lanes at both intersections. For each count, the actual traffic flow structure entered into the model was determined. Data collection locations are shown in Figure 3.

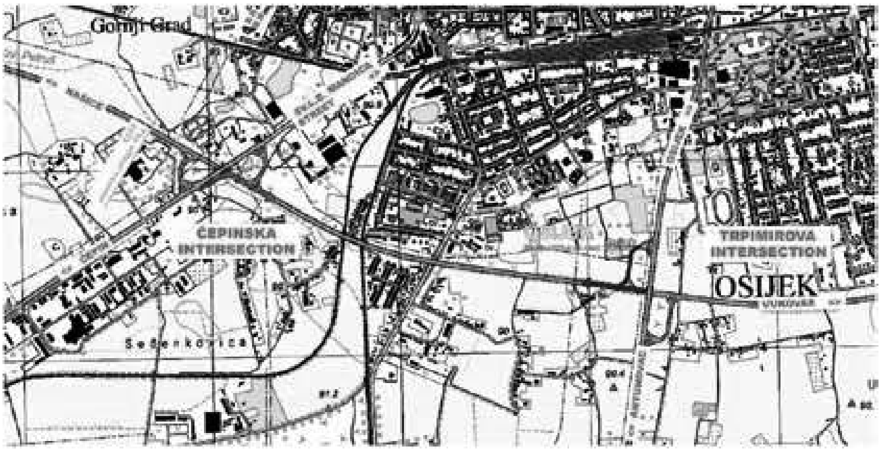

Figure 3: Positional plan of counters
Source: [24]

The results obtained by manual counting are compared with the data of the official Croatian Road 2525 Osijek south bypass counter and a good match with peak hours traffic is observed. Manual counting of traffic loads (Table 1 and 2) was used as input data to simulate the existing traffic flow. The analysis of data collected by manual traffic counting and data obtained from the official counter shows that the average daily traffic (ADT) is about 12,500 vehicles. Out of the total ADT, approximately 7,300 vehicles participated in peak hours, when the manual traffic counting was performed, which is 58.4% of the total daily traffic. By analysing the data from the official counter, it was found that an average percentage of 25% of vehicles were moving in the overtaking lane. The results of the count indicated what the morning and afternoon peak hours were and the critical peak hour was selected as the relevant one for further analysis. The results of the traffic load for the morning and afternoon peak hours for the Čepinska intersection are shown in Table 1 and the graphical interpretation of the traffic load for the relevant peak hour is shown in Figure 4.

Table 1: Manual traffic count data, Čepinska intersection, direction Našice - Vukovar

Time	**The main traffic lane - Našice - Vukovar**						**The entering ramp - Čepinska - Vukovar**					
	1	**2**	**3**	**4**	**5**	**Σ**	**1**	**2**	**3**	**4**	**5**	**Σ**
7-8 a.m.	*2*	*1416*	*148*	*80*	*10*	*1656*	*2*	*448*	*18*	*6*	*0*	*474*
3-4 p.m.	*14*	*1462*	*120*	*108*	*4*	*1708*	*10*	*520*	*22*	*6*	*2*	*560*
Total	**16**	**2878**	**268**	**188**	**14**	**3364**	**12**	**968**	**40**	**12**	**2**	**1034**
Types of vehicles: 1-motorcycle, 2-passenger cars, 3- trucks, 4- heavy trucks and 5- buses ***Input data for Vissim***												

Source: Authors

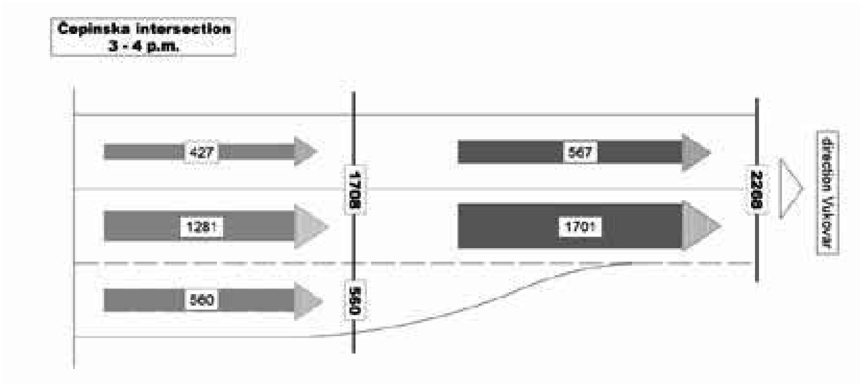

Figure 4: Results of manual traffic count data, Čepinska intersection
Source: [24]

For the intersection of Trpimirova, the results of the count are shown in Table 2, and a graphical interpretation of the traffic load of the relevant peak hour is shown in Figure 5.

Table 2: Manual traffic count data, Trpimirova intersection, direction Vukovar - Našice

Time	The main traffic lane - Vukovar - Našice						The entering ramp - Trpimirova - Našice					
	1	**2**	**3**	**4**	**5**	**Σ**	**1**	**2**	**3**	**4**	**5**	**Σ**
7-8 a.m.	*12*	*1446*	*130*	*76*	*10*	*1674*	*0*	*322*	*14*	*2*	*6*	*344*
3-4 p.m.	*10*	*1618*	*80*	*94*	*4*	*1806*	*2*	*426*	*12*	*4*	*2*	*446*
Total	**22**	**3064**	**210**	**170**	**14**	**3480**	**2**	**748**	**26**	**6**	**8**	**790**
Types of vehicles: 1-motorcycle, 2- passenger cars, 3- trucks, 4- heavy trucks and 5- buses ***Input data for Vissim***												

Source: Authors

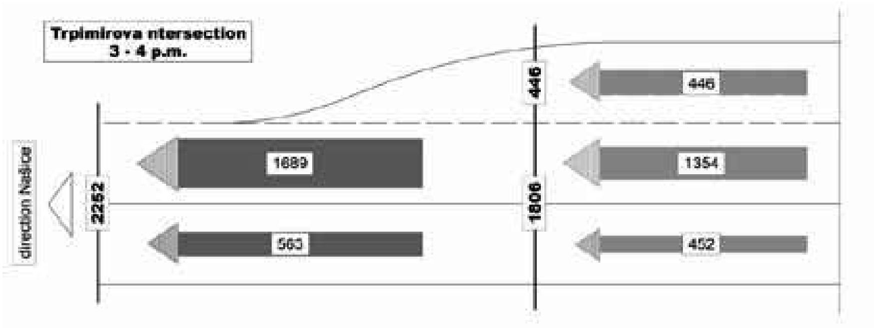

Figure 5: Results of manual traffic count data, Trpimirova intersection
Source: [24]

For the purpose of realistic speed modelling of each vehicle category, speeds were recorded at selected cross sections (mean time velocity). Speeds were measured by the police radar (Tuesday, 15th May, 2018) and the results are shown in Table 3. Speeds at the Čepinska intersection were recorded between 11 a.m. and 11.40 a.m. and at the Trpimirova intersection between 11.50 a.m. and 12.30 p.m.

Table 3: Mean time velocity (kilometre per hour), Čepinska and Trpimirova intersections

Intersection	Time	The main traffic lane					The entering ramp				
		1	2	3	4	5	1	2	3	4	5
Čepinska	***11-11.40 a.m.***	72	90.30	84.94	75.76	-	-	55.36	44.73	46.0	-
Trpimirova	***11.50 a.m.-12.30 p.m.***	-	90.02	69.19	70.67	78.33	-	47.74	40.6	35.0	-
Types of vehicles: 1-motorcycle, 2- passenger cars, 3- trucks, 4- heavy trucks and 5- buses ***Input data for Vissim***											

Source: Authors

4. Results

By applying the PTV VISSIM 10.0 microsimulation traffic model, traffic simulations were made for the observed acceleration lanes and the main traffic lanes at the intersections of Čepinska and Trpimirova. Forming the model base involves entries to be made of transport infrastructure geometric elements, conflict zones to be resolved by defining priority rules, and traffic routes to be entered for each traffic flow. Once formed, the model can be used to analyse different traffic scenarios defined by the input parameters and random numbers given by the random number generator (the same random seed generator value gives a repeatable traffic scenario). Input parameters are defined for each traffic load situation separately. The model does not generate strictly numerically defined traffic load, but considers the relative traffic load ratio of all traffic flows. The input data for the model of the current/future traffic situation are: the existing/assumed traffic load for the relevant peak hour, traffic structures and the mean value of speeds for individual vehicle categories. The mean time velocities of each vehicle category measured in the field represent the median of the normal velocity distribution, within this simulation model. The functional characteristics of the traffic flow selected as the output of the modelling are - average delays (sec/veh) and queue lengths (m). The average delay parameter is a user-oriented parameter and is often used in traffic analyses because it is directly related to the level of service. The maximum queue length parameter is selected because it is directly measurable in situ and often serves to validate the model.

Bearing in mind that the traffic flow is stochastic for each traffic load, ten different vehicle arrival scenarios were analysed. The results of average delays and queue lengths were obtained as mean values of all the analysed traffic scenarios.

4.1 Simulation results for existing traffic loads

The queue of vehicles does not appear for existing traffic loads, either in the model or in actual traffic conditions. By comparing the dynamics and conditions of the traffic flow in the simulation models formed versus those recorded in real traffic conditions at the observed locations, it can be concluded that the models realistically simulate traffic flows and priority rules and thus represent the first step of model validation.

Delay times are minimal, as can be seen from the simulation results shown in Figure 6. Vehicles flow in without stopping, and the low utilization of the total effective acceleration lane length of 250 meters indicates that the choice of merging point is affected by the current traffic situation.

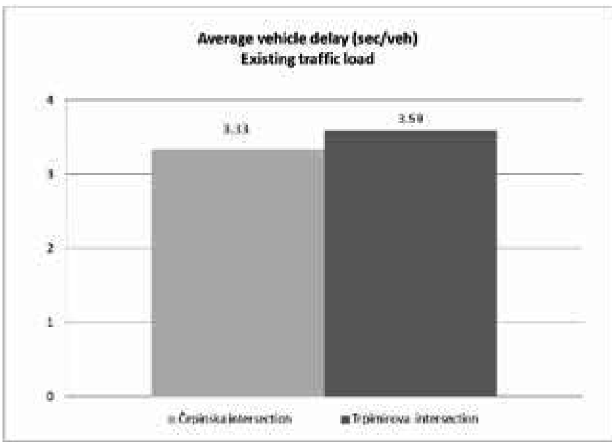

Figure 6: Average vehicle delay, existing traffic load [Source: Authors according to 24]

4.2 Simulation results for increasing traffic load

Within this paper, an analysis of various possible situations of increasing traffic load is made, with the aim of verifying whether the existing infrastructure meets future traffic requirements. The traffic load of the main flow had been increasing by the same traffic load of the secondary flow, and the situation of the increase of the traffic load and the main and secondary traffic flows was analysed.

4.2.1. Increasing the traffic load of the main flow

By increasing the main flow traffic load (up to 60%), according to the simulation results, the traffic situation remains similar to the existing traffic load. No vehicle queues are being formed and the existing length of the acceleration lane provides ample space for smooth inflow. The maximum percentage of vehicles flowing in at the section up to 150 meters in length, resulting in occasionally reduced vehicle speed in the acceleration lane in anticipation of the time gap to merge. The simulation results are shown in Figure 7.

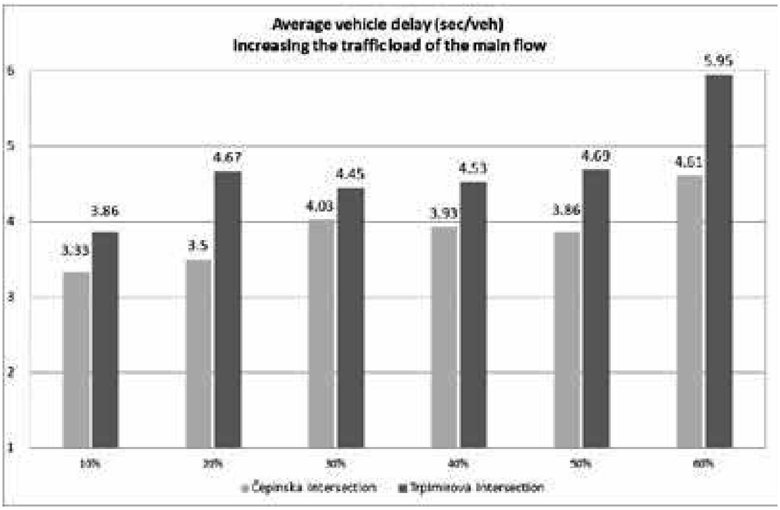

Figure 7: Average vehicle delay, increasing the load of the main flow [Source: Authors according to 24]

4.2.2. Increasing the traffic load of the main and secondary flow

A great number of different combinations of traffic load increases were analysed. The increase in traffic was analysed up to a 60% increase for both vehicle traffic flows (main and secondary flows) and the simulation results show that the secondary stream flows in without major difficulties and with incomplete utilization of the existing length of the acceleration lane. Higher traffic loads result in occasional delays and queues of vehicles consisting of 5-6 vehicles, often due to unused total length of the acceleration lane. Delay times and maximum queues of vehicles under conditions of increased traffic in the analysed volume do not pose a problem, either by the criterion of functional characteristics or by the criterion of traffic safety.

The analysis of individual variants reveals that the vehicles from the secondary traffic flow take the priority by force when flowing into the main flow, even when the real traffic conditions are not critical. Simulation of such situations indicates that the microsimulation program simulates the real behaviour of drivers in traffic. Additional adjustments to the real behaviour of drivers in local conditions can be made by adjusting the temporary lack of attention parameter described through two characteristics - duration and probability.

The results of the analysed traffic loads and their influence on the functional characteristics are shown in Figures 8 and 9.

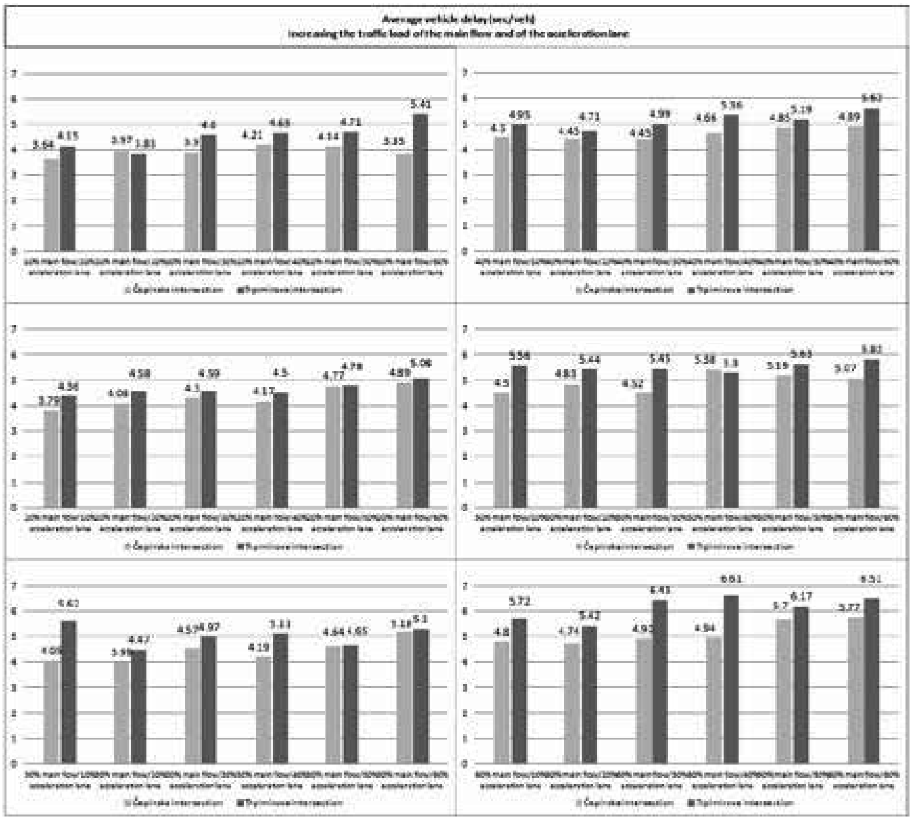

Figure 8: Average vehicle delay, increasing the traffic load of the main and secondary flow [Source: Authors according to 24]

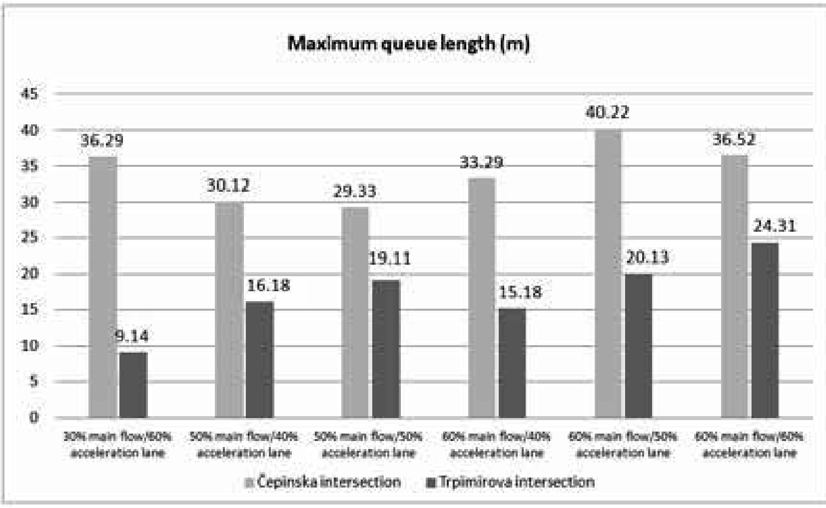

Figure 9: Maximum queue lengths for 250 m length of the acceleration lane
Source: Authors

4.2.3. Analysis of different what-if scenarios

One of the main advantages of simulation tools is the ability to analyse different what-if scenarios, not only in terms of different traffic loads or traffic regulations, but also in terms of optimization and design of transport infrastructure. Considering that in all the analysed traffic situations full length of the acceleration lanes at both intersections remained unused, the effect of reducing the length of the acceleration lanes was considered. The influence of 200 and 150 meters in length upon functional characteristics of the traffic flow was analysed using the microsimulation model. A length of 150 meters is the design recommendation [2] for the minimum effective acceleration lane length (Lg, Figure 1) for this road category.

The effect of reducing the length of the acceleration lane in conditions of the existing traffic load was analysed, as well as in conditions of the increasing the traffic load for those combinations of increasing loads that showed the greatest influence on functional indicators for the existing length of the acceleration lane. With the 200-meter acceleration lane length, the traffic continues to run smoothly, as can be seen from the results of the simulations shown in Figures 10 and 11.

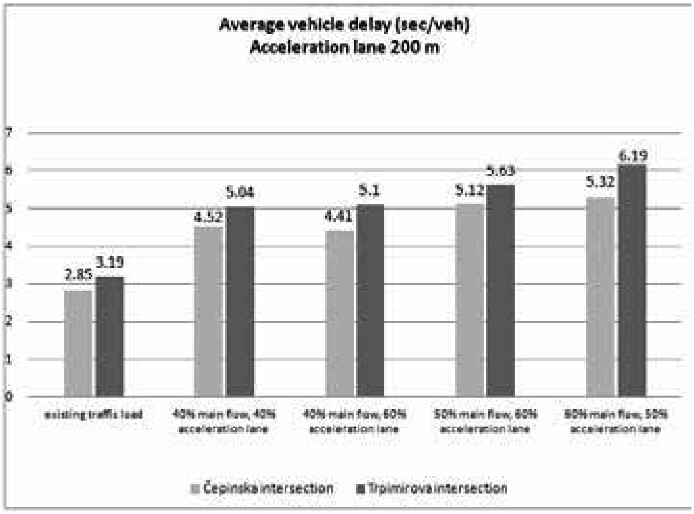

Figure 10: Average vehicle delay, 200 m length of the acceleration lane [Source: Authors according to 24]

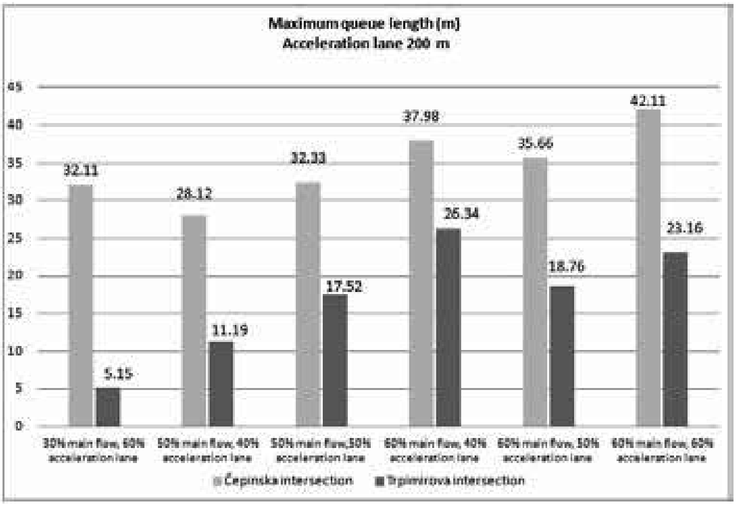

Figure 11: Maximum queue lengths,
200 m length of the acceleration lane [Source: Authors]

For the 150-meter acceleration lane length, one can clearly see a greater fluctuation of traffic flows and a decrease in the merging area. By observing the simulation, it is clear that the merging manoeuvre is being performed more aggressively. Drivers behave according to the available length of acceleration lanes and under non-critical traffic conditions (significant capacity reserve), the effect on functional indicators is not significant.

In some traffic scenarios, there is a reduction in speeds and a complete stop of the vehicles in the acceleration lane, due to the waiting time gap in the main traffic flow, but without utilizing the full length of the acceleration lane. Most vehicles stop in the first 50 meters and wait for an adequate time gap, thus creating queues of vehicles. On the one hand, this indicates an incomplete utilization of the acceleration lane length, but such behaviour has its logical basis in the parameters of traffic safety. Waiting for a time gap at the end of the acceleration lane gives more vehicles sufficient visibility into the lane of the main traffic stream. In conditions of a longer queue of vehicles and a longer waiting time, this would potentially create the opportunity for more aggressive drivers in the queue to take advantage of the time gap by "cutting the queue", thus endangering the vehicle that is first in the waiting line of the time gap. Although such driver's behaviour is improper, in actual traffic conditions the disabling principle has proven to be more effective than the sanctioning principle.

In the context of a significant increase in traffic load, worldwide experience has shown positive effects of ramp metering - the introduction of a combination of traffic lights and time gap detectors in the main flow. Such regulation allows a certain number of vehicles to flow in from the secondary flow, which correlates with the size of the time gap in the main flow.

The outputs of the simulations - the mean delay time and the maximum length of the queue of vehicles - are shown in Figures 12 and 13. These outputs clearly indicate that in existing traffic conditions, a 150-meter acceleration line length does not present a functional problem, but due to the influence on drivers' behaviour, it presents a problem due to safety parameters.

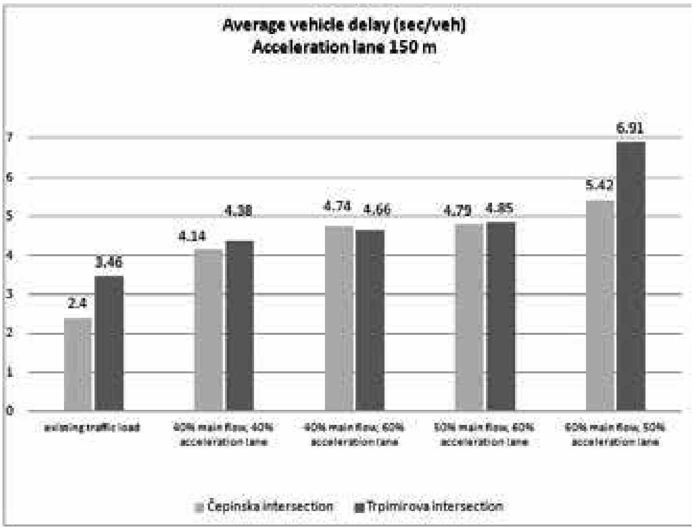

Figure 12: Average vehicle delay, 150 m length of the acceleration lane [Source: Authors according to 24]

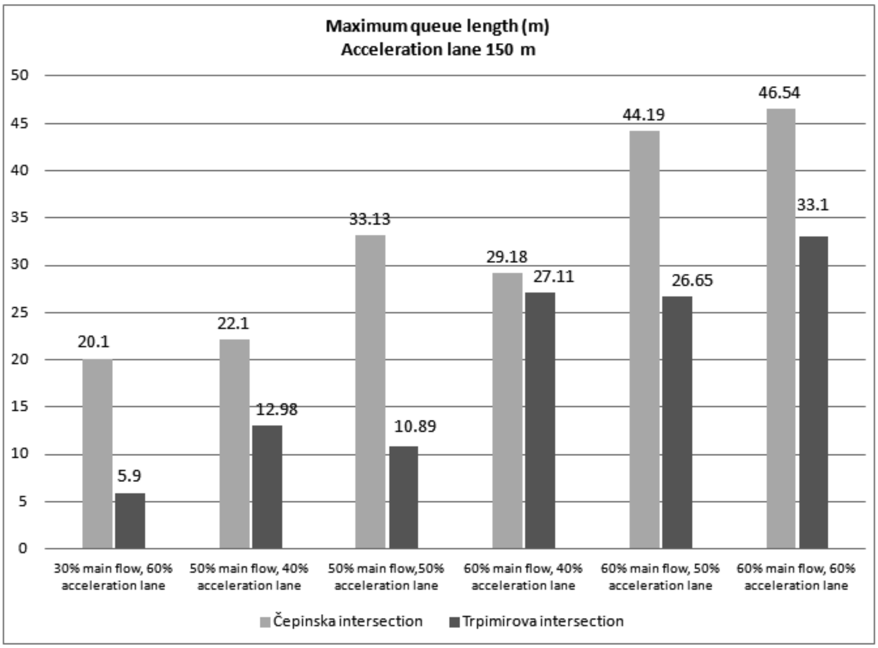

Figure 13: Maximum vehicle queue lengths, 150 m length of the acceleration lane [Source: Authors]

5 Discussion and Conclusion

The design elements of city roads and even high-speed roads have their own peculiarities in relation to out-of-city roads. Tightened spatial relationships, multimodal requirements and ecological criteria give each site a challenging and specific nature. The focus of this paper is to analyse the effective acceleration lane length, as an integral part of the urban highway transport infrastructure. The use of microsimulation enables optimization of the acceleration lane length for existing and future traffic demand.

The case study was made for two selected acceleration lanes on the southern bypass of the city of Osijek that were constructed in an effective length of 250 meters. Data collection was done in the field at both locations, data on the traffic load and traffic flow structure were collected, and speeds of each vehicle category in the main and secondary traffic flows were measured. The analysis of the observed elements of the transport infrastructure was made using the microsimulation tool VISSIM. Two indicators - average vehicle delays (sec/veh) and maximum queue lengths (m) - were selected to evaluate the functional parameters of each acceleration lane observed. Visual validation of the model was performed by comparing the vehicle flow dynamics under actual traffic conditions.

The simulation results show that in conditions of the existing traffic load there is a sufficient time gap in the main stream, the vehicles from the secondary stream flow in without stopping and creating queues, the merging area is in the first 150 meters, and that the average delays are small. Using the model, it is possible to analyse any increase in the main and secondary traffic flow and it can be used to analyse any traffic growth projection. In a 5 years' time horizon, provided revitalization of Osijek as a traffic node that will connect the gravitational traffic to the Vc highway corridor to the Hungarian border, the traffic load is expected to increase by up to 60%. Different combinations of increased traffic load up to 60% for both the main and secondary traffic flow were analysed using microsimulations. The selected functional indicators for the existing length of both acceleration lanes do not indicate any significant problems for any of the analysed combinations of traffic load increases (up to 60%). Smaller queues of 5-6 vehicles are created on the secondary flow, and average delays are nothing more than 6.5 sec/veh (Table 4). Due to the larger traffic load of the main flow, the merging area is increased, but still most of the vehicles from the secondary flow merge with the main flow up to 200 meters in length. The results of the analysis of different traffic scenarios for the existing acceleration line length of 250 meters are shown in Table 4.

Table 4: The results of analysis of different traffic scenarios - acceleration line length 250 m

Traffic load	M/S* (% / %)	average vehicle delays (sec/veh)		maximum queue lengths (m)	
		Čepinska	Trpimirova	Čepinska	Trpimirova
existing load	-	3.3	3.6	-	-
increase in main flow	60/-	4.6	6.0	-	-
increase in main and secondary flow	60/60	5.8	6.5	36.5	24.3
	60/50	5.7	6.2	40.2	20.3
*M/S = % increase in the main traffic flow / % increase in the secondary flow					

Source: Authors

The use of microsimulation allows the analysis of different what-if scenarios and thus the impact of reducing the effective length of the acceleration lane to 200 meters and 150 meters at both locations for different traffic load combinations was analysed (Table 5).

Table 5: The results of analysis of different traffic scenarios

Traffic load	M/S (% / %)	average vehicle delays (sec/veh)		maximum queue lengths (m)	
		Čepinska	Trpimirova	Čepinska	Trpimirova
acceleration line length 200 m					
increase in main and secondary flow	60/60	5.3	6.2	42.1	23.2
	60/50	5.1	5.6	35.7	18.8
acceleration line length 150 m					
increase in main and secondary flow	60/60	5.4	6.9	46.5	33.1
	60/50	4.8	4.9	44.2	26.7

Source: Authors

The results for a 200-meter acceleration lane length do not show any significant difference from the results for the existing 250 m length in any location (Table 5). For a 150-meter acceleration lane, greater fluctuation in traffic flows can be clearly seen, and a reduction of the acceleration lane length has a psychological effect on drivers' behaviour, making them perform the merging manoeuvre more aggressively. Drivers behave according to the available length of acceleration lanes and under non-critical traffic conditions (significant capacity reserve), and the effect on functional indicators is not significant. Smaller vehicle queues are created, smaller delays and mean time losses amount to no more than 7 sec/vehicle (Table 5). For all traffic scenarios analysed within this paper, average time delays do not exceed 10 seconds per vehicle, which gives the highest "A" level of service. The simulation results show that under the existing traffic conditions, the 150-meter length of the acceleration lane is not a problem according to the functional parameters, but because it influences the drivers' behaviour, it represents a problem according to the safety parameters.

In the continuation of the research, it is necessary to analyse the impact of increasing the share of freight traffic in the traffic flow structure, as well as the increase in the number of heavy goods vehicles on conditions of merging traffic flows.

The existing length of 250 meters provides a high level of safety with respect to road rank and permitted speeds, and provides a length reserve for the needs of new traffic requirements and regulations (e.g. ramp metering). Strategies for the development of transport in European countries are planning to introduce new technologies in transport, primarily in the freight transport, through the introduction of computer-controlled queues of freight vehicles. The basic prerequisite for the implementation of new transport strategies and technologies is that the existing transport infrastructure is not restrictive.

The aim of this paper was to demonstrate the applicability of microsimulation modelling in optimizing the design elements of the traffic infrastructure on the example of the urban highway acceleration lane length.

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