Microsimulation of pedestrian conflict with other transport modes

J Růžička¹, J Kruntorád² and R Rek¹

¹Department of Transport Telematics, Czech Technical University in Prague Faculty of Transportation Sciences, Konviktská 20, Prague 1, 110 00, Czech Republic
²Department of Transportation Systems, Czech Technical University in Prague Faculty of Transportation Sciences, Konviktská 20, Prague 1, 110 00, Czech Republic

Abstract. An effective solution of the conflict points of different transport modes is a significant issue at the urban level today. With the permanent increase of traffic in cities, it is necessary to look for suitable and sustainable transport solutions to these situations, so that the traffic flow is smooth and the transport remains safe, ecological and economical. The paper deals with the design of a simple decision-making tool for selecting the solution of pedestrian conflict with other traffic modes (classical pedestrian crossing, controlled pedestrian crossing for defined pedestrian and vehicle flows, based on experimental microsimulation. High pedestrian flows their dependence on the delay time of road users are not properly implemented in Czech legislation. The results are verified in a case study of conflict solution within the reconstruction of a public transport terminal in Prague.

1. Introduction

One of the problems of cities today is induced traffic [1]. When a new capacity connection is created (e.g., a new motorway, pedestrian zone, bus or railway line, or a network of cycle paths), it will usually raise demand for this capacity. This phenomenon in transport sometimes causes traffic conflicts that need to be properly solved. Traffic conflict is a situation where there is a collision of different modes of transport in one place. A frequent solution in densely populated and built areas is the use of telematics systems, the main benefits of which are to increase transport safety and fluency as a whole and to reduce economic costs and externalities of transport. The research focuses on the conflict of pedestrians with other modes of transport with a focus on road transport and aims to propose general recommendations for solving traffic conflicts in previously known situations. This conflict can be solved in several ways, using an extra-level or level solution. However, extra-level solutions are expensive, so the article focuses more on level solutions, which can be the establishment of an uncontrolled pedestrian crossing, crossing points, a controlled pedestrian crossing with demand button, and a controlled pedestrian crossing without demand button. The paper mainly focuses on selecting a suitable solution based on a high pedestrian flow rate. The chosen research methods are mainly the method of searching for current knowledge from the Czech Republic and abroad (both research papers and valid technical standards), followed by the method of experimental microsimulation.

The article is logically structured. In the following chapter, "State of the art" the topic is viewed from a scientific perspective, and the main conclusions from the research conducted by the authors are used. The chapter "Methodology" follows, describing the progress of activities over time. The chapter "Results" then verifies the suitability of the proposed procedure for a specific case study of the reconstruction of the public transport terminal in Prague Černý Most.
2. State of the art
This part of the article summarizes the broader context of the Czech legislation issues from the point of view of the conflict between pedestrian and vehicle traffic. Subsequently, the authors will focus on the search for trends in the field of microsimulation of pedestrians and the solution of conflicts with pedestrians.

2.1 The conflict between pedestrian and vehicle traffic in Czech legislation
The technical standard ČSN 73 6110 Design of urban roads [2] defines the basic rules for the application of individual types of pedestrian level crossing in intersection sections with a permitted speed of 50 km/h, which can be seen in Figure 1 below. The pedestrian flow of pedestrians crossing a road is related to the flow rates of vehicles. Based on this relation, the solution according to Figure 1 is categorized as follows:

- A: no-conflict solution method is required;
- B: a pedestrian crossing or crossing point is proposed with possible construction adjustment (narrowing of lanes, elevated areas, etc. – possible combination of elements);
- C: a pedestrian crossing with a pedestrian island is proposed;
- D: a signal-controlled pedestrian crossing is proposed.

![Figure 1. Conflict solution of pedestrians and vehicles depending on the input vehicle flow and the pedestrian flow according to [2].](image-url)

It can be seen from Figure 1 that while for the vehicle flow rate the given measure is defined relatively exactly, the pedestrian flow ends at the value of 500 pedestrians and is not solved further. In densely populated agglomerations, however, these values of pedestrian flow are often exceeded at the peak, so it is appropriate to deal with the opposite situation: the sensitivity of high pedestrian flows to conflict.

The second relevant document is TP 81 – Design of traffic lights for road traffic control [3] dealing with specific cases where it is useful to design traffic lights on roads. It is the situation where the traffic flow at the crossing reaches values higher than during rush hours of the day:

- 1,100 veh/h – crossing over a single-lane or double-lane road,
- 1,000 veh/h – crossing over a three-lane road,
- 900 veh/h – crossing over a four-lane (or exceptionally multi-lane) undivided road;

Therefore, it can be noted that even these technical standards do not take into account the pedestrian flow rate across pedestrian crossings.
2.2 Microsimulation of pedestrian and vehicle conflict in science and research

[3] describes the factors affecting pedestrian behaviour divided horizontally into measurable and unmeasurable factors and vertically into internal and external factors. [5] focuses on macroscopic models, specifically on larger integrated areas and their control, and on microscopic models dealing with the model of areas of individual intersections or the interaction of vehicles or pedestrians with each other. The use of these models in simulation software is widespread, for example, in predicting the conflict of vehicles with pedestrians at pedestrian crossings, where the results of [5] confirmed that it is possible to use simulation software to predict conflict points with some reasonable deviation. The number of observed and simulated conflicts was reasonably confirmed in a case study in Doha in the State of Qatar. The result was also confirmed in [6], which, unlike the previous one, differs in testing at a signalized intersection. However, the result was the same finding that the number of potential points of conflict was relatively the same as the number of points of conflict observed. The use of this simulation software to reduce potentially dangerous places is one of the ensuing advantages because it is possible to predict dangerous places from their result before their construction. By techniques combining microsimulation and automatic conflict analysis SSAM (Surrogate Safety Assessment Model), it is possible to minimize conflict points and find better solutions and especially to study and evaluate different types of road crossings (roundabouts, traffic lights, and unregulated intersections), which can determine the optimal security level solutions, as shown in [7]. Setting up, calibrating and validating a model in these virtual environments is a major barrier to making all models reliable and usable. Therefore, some researchers focus on improving the quality of these models from real-world measured data from interactions between pedestrian crossings at intersections and vehicles approaching them [8], from interactions between pedestrians at crossings or when crossing two oncoming pedestrian flows in confined spaces [9], [10], or even a combination of both variants in addition to the environment, the type of intersection, another type of vehicle, etc. [11],[12] therefore deals with a multimodal simulation model for the study of mixed transport, the result is a microsimulation model, which focuses on the interaction behaviour of pedestrians and vehicles, which according to the authors can be used as a basis for microsimulation models that address similar issues. Another way to significantly improve the quality of the models is to examine the behaviour of pedestrians. One of the obstacles to the accuracy of simulations in the area of traffic conflict simulation is limited models of pedestrian behaviour, which are inherently very complex. [13] deals with the methodology of pedestrian behaviour at crossings to improve the quality of these models to improve pedestrian models in simulation software. A conflict between pedestrians and vehicles at high flows is discussed in [14]. Simulation of pedestrians crossing at a high pedestrian flow rate (exceeding 25,000 ped/h) due to an event (around the stadium) in Madinah showed a clear pedestrian delay when crossing. At the same time, the vehicle delay caused by high pedestrian traffic was assessed. Subsequently, various strategies for resolving this conflict were proposed, which included both a level solution (in the form of modification of signal plans or ban of vehicles entering the stadium area) and an extra-level solution (in the form of a pedestrian tunnel).

3. Methodology

The research aims to verify by a microsimulation experiment on a model the conflict between pedestrians and vehicles to verify the influence of input values of pedestrian flow exceeding 500 pedestrians per hour and vehicle flow not exceeding 500 vehicles per hour on the values of output variable delay time of pedestrians and vehicles in place before the conflict on classical pedestrian crossing without traffic control. The basic premise is that pedestrians experience minimal delays due to their advantage and vehicles gradually experience greater delays with higher pedestrian and vehicle flow rates. Assuming high pedestrian flows, even lower vehicle flow rates will be sufficient to create vehicle congestion in the model when the pedestrian crossing is handled classically. The purpose of the experiment is to generalize its results for determining the critical values of pedestrian flow and vehicle flow rate in conflict, where it is already appropriate to solve the situation in a different way than with a level crossing for pedestrians, i.e. mainly by traffic lights or extra-level solutions. The model situation has the following setting parameters: The simulation is performed in the PTV VISSIM. The pedestrian crossing intersects a two-lane two-way road with a total width of 8 meters, which is 4 meters wide as
standard, the entry of vehicles into the model network is located 400 meters before the pedestrian crossing. The behaviour model is used by Wiedemann 95. The velocity models were taken from the VISSIM program. The entry of vehicles is random, with all vehicles coming from one direction, the entry of pedestrians into the network is also random, and pedestrians come evenly from both directions to the place of conflict. The distribution of pedestrians and vehicles in time is uniform. The combinations of pedestrian and vehicle input flow rates were changed during the simulation and the dependence of pedestrian and vehicle delay time on these combinations was investigated. Verification of these results occurred on a real example of microsimulation of the planned new solution of the "Černý Most" terminal in Prague. Input data were entered into the simulation on the basis of our own traffic survey, the course of which is described in more detail in the chapter with the case study.

4. Results
The results of the experiment can be read from Table 1. The simulation was repeated thirty times for each combination of inputs. For each simulation, a set of delay times of individual vehicles and individual pedestrians before the conflict crossing for two hours was generated and their average value was calculated (using the arithmetic mean). The resulting value, "Average Pedestrian Delay," is then the average of all replicates of the experiment. The value "Number of Unloaded Vehicles Due to Congestion" is then the average value of the number of vehicles that were not loaded into the simulation at all due to the resulting column, which reached the entry of vehicles into the network (greater than 400 meters).

| Input: Pedestrian flow [ped/h] | Input: Vehicle flow [veh/h] | Output: Average Pedestrian Delay [s] | Output: Average Vehicle Delay [s] | Number of Unloaded Vehicles Due to Congestion [-] |
|-------------------------------|----------------------------|--------------------------------------|----------------------------------|-----------------------------------------------|
| 500                           | 50                        | 0.88                                 | 6.78                             | 0                                             |
| 500                           | 100                       | 0.95                                 | 5.73                             | 0                                             |
| 500                           | 150                       | 1.03                                 | 7.17                             | 0                                             |
| 500                           | 200                       | 1.13                                 | 8.48                             | 0                                             |
| 500                           | 300                       | 1.30                                 | 11.53                            | 0                                             |
| 500                           | 500                       | 1.65                                 | 25.54                            | 0                                             |
| 1,000                         | 50                        | 1.04                                 | 11.26                            | 0                                             |
| 1,000                         | 100                       | 1.16                                 | 13.74                            | 0                                             |
| 1,000                         | 150                       | 1.25                                 | 19.24                            | 0                                             |
| 1,000                         | 200                       | 1.39                                 | 26.28                            | 0                                             |
| 1,000                         | 300                       | 1.63                                 | 59.34                            | 0                                             |
| 1,000                         | 500                       | 1.60                                 | 62.01                            | 420                                           |
| 1,500                         | 50                        | 1.25                                 | 26.52                            | 0                                             |
| 1,500                         | 100                       | 1.41                                 | 38.21                            | 0                                             |
| 1,500                         | 150                       | 1.53                                 | 87.60                            | 0                                             |
| 1,500                         | 200                       | 1.60                                 | 118.39                           | 0                                             |
| 1,500                         | 300                       | 1.60                                 | 117.33                           | 268                                           |
| 1,500                         | 500                       | 1.60                                 | 117.38                           | 683                                           |
| 2,000                         | 50                        | 1.50                                 | 65.03                            | 0                                             |
| 2,000                         | 100                       | 1.64                                 | 186.34                           | 0                                             |
| 2,000                         | 150                       | 1.67                                 | 207.08                           | 72                                             |
| 2,000                         | 200                       | 1.67                                 | 209.95                           | 180                                           |
| 2,000                         | 300                       | 1.67                                 | 200.48                           | 388                                           |
| 2,000                         | 500                       | 1.68                                 | 201.94                           | 805                                           |

The following summary can be drawn from the experiment. At a given pedestrian flowrate of 500 pedestrians/hour and a changing vehicle flow rate in the range of 50-500 vehicles/hour, there is a very small increase in pedestrian delay in the tens of a second and a relatively small increase in vehicle delay from seconds to tens of milliseconds. It can be stated that at these flow rates the level solution of
the pedestrian crossing is stable, although at higher flow rates the level of service for vehicles decreases slightly.

At a given flow rate of 1,000 pedestrians/hour and a changing vehicle flow rate in the range of 50-500 vehicles/hour, there is a very small increase in pedestrian delay, but a higher increase in vehicle delay in the tens of milliseconds range. The increase then stops at values of around 60 seconds, which is because at a vehicle flow rate of 300-500 vehicles per hour, a critical point occurs and the formation of such a long traffic queue that some vehicles can no longer be loaded into the network.

At a given flow rate of 1,500 pedestrians/hour and a changing vehicle flow rate in the range of 50-500 vehicles/hour, there is still a very small increase in pedestrian delay, but a high increase in vehicle delay. When the vehicle flow rate exceeds 200 vehicles per hour, a critical point occurs and there is the formation of such a long traffic queue that some vehicles cannot be loaded into the network.

At a given flow rate of 2,000 pedestrians/hour and a changing vehicle flow rate in the range of 50-500 vehicles/hour, there is again a very small increase in pedestrian delay in tens of milliseconds as the vehicle flow rate increases, but a high increase in vehicle delay. The critical point when the vehicles could not be loaded into the simulation in this case is 100 vehicles per hour.

The described situation is graphically illustrated in Figure 2. At higher pedestrian flows, there is a sharper increase in delay, higher delay values, earlier stagnation of the curve, and at that moment when the curve stagnates, a traffic queue forms in front of the place of conflict. It should be emphasized that the curves for high intensity values converge because some vehicles could not be loaded into the simulation. Otherwise, of course, the residence time would increase to even higher values.

![Figure 2](image-url)

**Figure 2.** Dependence of the delay time of increasing vehicle flow rate on defined pedestrian flow – pedestrian crossing without signal control.

Furthermore, a comparative experiment was performed, in which the same situation was simulated for a pedestrian crossing controlled by a fixed signal plan. The fixed signal plan was set for a cycle of 60 seconds, giving both pedestrians and vehicles the same green time. It can be seen from Figure 3 that in the case of this solution, the delay time of vehicles does not depend on pedestrian flow and the solution is suitable in all cases, although the level of service decreases with higher vehicle flow rates. Of course, when solving a controlled pedestrian crossing, there are higher values for pedestrian delays, in the average range \(<12,16>\) seconds. When the vehicle a pedestrian flow rates are increased, the average delay increases in hundredths of a second.
Figure 3. Dependence of the delay time of increasing vehicle flow rate on the defined pedestrian flow – signal-controlled crossing.

5. Case study – Černý Most terminal

The dependence of a suitable choice of conflict resolution can be summarized based on our experiments in the form of Table 2 below. The table answers the question for which values of pedestrian and vehicle flow rates it can still be considered in terms of capacity, classical pedestrian crossing (“YES” values) and for which it is already necessary to look for other solutions, such as traffic control or pedestrian bridge (“NO” values).

Table 2. Decision on the choice of conflict resolution based on input flow rates.

| Vehicle flow rate [veh/h] | 0-50 | 50-100 | 100-200 | 200-300 | 300-500 | 500 and more |
|---------------------------|------|--------|---------|---------|---------|--------------|
| Pedestrian flow rate 500  | YES  | YES    | YES     | YES     | YES     | NOT CHECKED |
| Pedestrian flow rate 1,000| YES  | YES    | YES     | YES     | NO      | NO           |
| Pedestrian flow rate 2,000| YES  | NO     | NO      | NO      | NO      | NO           |

Verification of these results occurred on a real example of microsimulation of the planned new solution of the "Černý Most" terminal in Prague. As part of the new solution, the bus terminal is moved to the metro level in Černý Most, which, however, results in new conflicts between buses and pedestrians at level crossings. Concerns about the resolution of these conflicts are justified. On average, about 34,000 pedestrians enter the metro at the Černý Most station on a normal non-holiday Wednesday, 30,000 then leave it on the same day. The bus terminal will serve an average of around 2,500 buses from 6:00 to 20:00. The most fundamental conflict in the new solution occurs at the central pedestrian crossing that connects the metro to the area of the Černý Most residential area. In addition, level crossings are created at two other locations within the terminal at a distance of about 50 meters from the central crossing. To give relevant input to the microsimulation, a traffic survey must first be carried out to detect the vehicle flow rate at the terminal (buses) and the pedestrian flow rate through individual pedestrian crossings. The future bus rate estimation was determined based on current transport data so that it should not exceed a flow rate of 200 veh/h during peak hours. To determine the pedestrian flow rate, the pedestrian traffic survey was conducted in April 2021, however, faced with older data, which were not affected by the situation around the COVID-19 pandemic. Thus, the established coefficients resulted in a more...
realistic situation for future years. As a result, at peak times, pedestrian flows at the central crossing will exceed 2,000 ped/h, while at secondary crossings they will generally not reach values greater than 500ped/h. The simulation time was 2 hours. The example from the microsimulation in VISSIM can be seen in Figure 4.

Figure 4. The example of microsimulation of the described case study

Looking at Table 2, it can be assumed that while for the central crossing the level solution for vehicles does not meet the capacity and traffic congestion will occur, for secondary pedestrian crossings the level solution will be sufficient due to the lower flow rate. After microsimulation, this assumption was confirmed. At the central pedestrian crossing, the network gradually becomes overcrowded, and a bus queue forms over time. In the case of associated pedestrian crossings, these will easily meet the input flow rate. Therefore, it is important to emphasize that in the case of pedestrian flows higher than 2,000 pedestrians, it does not make sense to think about the classic level crossing for pedestrians at all under the given conditions. Likewise, in this particular case, it does not make sense to consider an extra-level solution because the architectural purpose of the whole project is to have a metro and bus stop at one level for a more comfortable change compared to the existing solution.

Therefore, a traffic control is considered, where previous research has also shown that this solution will work. The case study also examines the differences between conflict management using fixed signalling plans and dynamic control of pedestrian or bus preference. The preference of selected road users is a very topical issue and research is still underway on which categories of road users should be preferred [15]. For the case study of the terminal in Černý Most, traffic control was finally recommended with the following more detailed comment: At the time between morning and evening rush hour, from the point of view of traffic control, dynamic control can be recommended in the form of a permanent green for pedestrians and a challenge for registered buses. During rush hour, the solution is not as clear, because there are quite a lot of registered buses, in contrast to the high pedestrian flow rate at crossings. A fixed signal plan then causes less delay for pedestrians than dynamic control because it creates regular clusters of buses and pedestrians are more likely to arrive at the green signal and conversely causes more delays for buses. However, thanks to the extension of the phase for buses, dynamic control can significantly reduce their delay and passage through the terminal, but at the expense of pedestrians who stay longer at the central crossing. The respective advantages and disadvantages for the individual parties must be well balanced in the final proposal. Side crossings are recommended to be solved by uncontrolled pedestrian crossings or crossing points. When implementing crossing points, bus delays are saved, pedestrian delays are minimal, but at the same time, this solution may be less safe for pedestrians.
6. Discussion and future work

As part of the research, a simple decision-making tool was created, which can serve high pedestrian flows with an easier decision to solve pedestrian conflicts with other road users. Given the assumption that similar conflicts will occur more frequently in larger cities, it might be appropriate to develop a similar tool at a much more detailed level of distinction and to implement it in Czech technical standards or technical requirements. This decision tool was verified in the model of the new terminal solution in the Černý Most case study and it can be assumed that it will be possible to use it for any further solution to the conflict between pedestrians and vehicles if the input flow rates are known. Of course, it is necessary to proceed individually in each case, because for these high numbers of pedestrians to cross two lanes road on crossing in a given time (one minute for controlled crossing) can reduce their safety. In the case of the considered case study, the advantage is the construction of other considered pedestrian crossings through the terminal near the main crossing controlled by traffic lights and the assumption of a slight distribution of pedestrian traffic between other crossings. It should always be considered whether the greater advantage for the given case is barrier-free and comfortable level solution, or, conversely, complete non-conflicting level crossing.

Acknowledgments

This article was supported by the Czech Technical University Grant Agency in Prague, grant No. SGS20/137/OHK2/2T/16 Behaviour of Pedestrians in Public Transport Terminals and on Access Roads to them.

References

[1] Næss, P, Nicolaisen, M S and Strand A 2012 Traffic Forecasts Ignoring Induced Demand: a Shaky Fundament for Cost-Benefit Analyses European Journal of Transport and Infrastructure Research 12 (3)
[2] 2006 ČSN 73 6110 Projektování místních komunikací, (Prague: Český normalizační institut) chapter 10 pp 60-66
[3] Martolos J et al 2015 TP 81 - Navrhování světelných signalizačních zařízení pro řízení provozu na pozemních komunikacích chapter 1 pp 9-11
[4] Filip J 2013 Vliv pěšího provozu na kapacitu úrovňových křížovek Disertation thesis (Czech Technical University in Prague Faculty of Transportation Sciences)
[5] Muley D, Ghanim M and Kharbeche M Prediction of Traffic Conflicts at Signalized Intersections using SSAM Procedia Computer Science 130 pp 255-262
[6] Wu J, Radwan E and Abou-Senna H Pedestrian vehicle conflict analysis at signalized intersection (Rio de Janeiro RS5C2016)
[7] Astarita V, Festa D C, Giofrè V P and Guido G 2019 Surrogate Safety Measures from Traffic Simulation Models a Comparison of different Models for Intersection Safety Evaluation Transportation Research Procedia, 37 pp 219-226
[8] Gorrini A, Crociani L, Vizzari G and Bandini S 2018 Observation results on pedestrian-vehicle interactions at non-signalized intersections towards simulation Transportation Research Part F: Traffic Psychology and Behaviour 59 pp 269-285
[9] Guo R-Y, Wong S C, Huang H-J, Zhang P and Lam W H K 2010 A microscopic pedestrian-simulation model and its application to intersecting flows Physica A: Statistical Mechanics and its Applications 389 (3) pp 515-526
[10] Asano M, Iryo T and Kuwahara M 2010 Microscopic pedestrian simulation model combined with a tactical model for route choice behaviour Transportation Research Part C: Emerging Technologies 18 (6) pp 842-855
[11] Zeng W, Chen P, Nakamura H and Iryo-Asano M 2014 Application of social force model to pedestrian behavior analysis at signalized crosswalk Transportation Research Part C: Emerging Technologies 40 pp 143-159
[12] Wang T, Wu J and McDonald M 2021 A micro-simulation model of pedestrian-vehicle interaction behavior at unsignalized mid-block locations 15th Int. IEEE Conf. on Intelligent Transportation Systems pp 1827-1833
[13] Hamed M 2001 Analysis of pedestrians’ behavior at pedestrian crossings. *Safety Science* **38** (1) pp 63-82

[14] Abdelgawad H, Shalaby A, Abdulhai B and Gutub A A 2014 A Microscopic modeling of large-scale pedestrian-vehicle conflicts in the city of Madinah *Journal of Advanced Transportation* **48** (6) pp 507-525

[15] Tichý T, Svorc D, Ruzicka M and Belinova Z 2021 Thermal Feature Detection of Vehicle Categories in the Urban Area. *Sustainability 2021* **13**