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PhD thesis book

Increasing pedestrians' traffic safety through design parameters

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1 THE SHORT DESCRIPTION OF THE RESEARCH, PREMILINARIES AND OBJECTIVES

The short description of the research and preliminaries

The movements and waiting's phenomena of pedestrians are a special part of city traffic. The pedestrians give different reactions in each situation; these reactions depend on the traffic, the age of the pedestrian, the gender, the health and from the disability of roads users. The weather, the limit of the traffic volume, an accident or a special event can influence them. I documented the importance of the topic in the thesis, and I show the national and the international researcher's results briefly.

I lay emphasis on those consequences during my research, which are the fundaments of my research. The relevant specifications, standards and manuals' main points are presented in the thesis. I built upon my research from international methods in pedestrian's behavior analysis at traffic lights and in longer green time suggestion. I analyzed stairways (effective width), zebra crossings and tramline platforms.

The number of accidents shows us the fact that the ratio of the pedestrian's accident is significant. The pedestrians are vulnerable road users. The pedestrians do not have to know the Highway Code (in Hungarian KRESZ). They cause 40% of the pedestrian accident. In 2010 died 192 pedestrians in Hungary. This value was in 2011 124, in 2012 156 and in 2013 147.

The fundamental objective of my research was to refine the previous analysis and relationships. I compared my results with these data (international and national measurements) at zebra crossings, zebra crossings with traffic light, stairways and tramline platforms. In some cases I made VISSIM microsimulations.

My analysis and design method help to improve the national specifications and support to introduce Level of Service categories, where there is no standard currently. The other objective of the thesis is to introduce level of service categories into zebra crossing's design and into tramline platforms. The Hungarian specifications do not have design method for tramline platforms; it gives only a minimum recommended width to the planners.

The structure of the thesis

The thesis has 8 main chapters. In *Chapter 1* I show the importance of the topic and the most important results of national and international researchers. In *Chapter 2* the relevant speculations, standards and manuals' main points are presented. I present the most important pedestrian and vehicle traffic correlations, definitions and equations in *Chapter 3*. The used pedestrian behavior parameters are collected, which are set in the VISSIM software. My own measurements' methods are presented briefly in this chapter as well. In *Chapter 4* I show the pedestrian behavior analysis at traffic light controlled zebra crossings and the renewing of the green time length. I analyzed the causes of the irregular pedestrian crossings. The other pedestrian facilities' analyses are presented in the *Chapter 5*. These facilities are the following: stairway, zebra crossing and tramline platform. The new scientific results are presented in *Chapter 6*, and I show the importance of my thesis. The *Chapter 7* presents the further research. In *Chapter 8* I collected the references and the list of publications related to the thesis.

2 THE METHOD OF THE RESEARCH

Based on measurement, observations and microsimulation's running I suggest renewing the Hungarian facility design methods. These data comes from my own flow counting (photo and video technology), which were built into the VISSIM. With VISSIM software the designers can check their plans for different vehicle and pedestrian combinations.

There are other modern methods, which are available. The punctuality of the data and the speed of the measurement are important. The public video records are late and not up-to-date, they change in each interval (e.g. 10-15 s). These records are no usable for detailed analysis.

The counting methods are slow and they need more counters. This method used only low passenger volumes tramline platforms. On other facilities I made video records, and at home I analyzed the records. I measured the pedestrians' speed, density, gender and elderly.

3 THE RELEVANT RESEARCH REFERENCES WHICH ARE ANALYSED PEDESTRIAN MOVEMENTS

The relevant pedestrians' researches comes from 1980th years, one of them is the Urban Transport Handbook [*Városi közlekedési kézikönyv* (1984)] and *Metro Handbook* [*Metró kézikönyv* (1982)]. The handbooks recommend for design process for some pedestrian facility as wheel. They give 2 categories for level of service: I. and II. (sufficient and tolerable). The fundamental diagrams and the previous research results can be found in them. The results are use in the Pedestrian undergrounds design specification [*Gyalogos aluljáró tervezési irányelvek]* and in the Hungarian [*ÚME, 2009*].

János Berényi in his Cs.C. dissertation analyzed pedestrian flow characteristics (*Berényi, 1988*). He used vide and photo technology for analyzing walkways, sidewalks and stairways, and used stochastic simulation for design these facilities. János Juhász work out am own simulation model (SIMAPAS), with which the traffic flow can be analyzed at zebra crossings and near to zebra crossings (*Juhász, 2007*). A study from 1990, which are made based on analysis from 1981 (*FKBT, 1990*) shows, that the average pedestrians speed at zebra crossings are lower than at signalized zebra crossings.

The result of Thobias Kretz was built into VISSIM software. In 2012 in a research with Johansson they present the calibration of moving pedestrian moving in crowded situation (*Johansson et al., 2012*). The foundation of the model ('Social Force') comes from Helbing&Farkas from 1995 (*Helbing et al., 1995, Johansson& Helbing 2007*). This model is used in VISSIM. Weidmann's publication presents the pedestrian relationships (*Wiedemann, 1993*), as Professor Knoflacher he shows the most important pedestrian parameters, the experiences on the main facilities. We can found in Knoflacher's book (*Knoflacher, 1995*) and in Schopf's (*Schopf, 1985*) dissertation more relationships, which are very interesting. The pedestrian speed depends on various factors, e.g. the height of the pedestrian, the size of group and the grade of the ramp. Winnie Daamen has the newest connected research from Netherland. The PhD dissertation presents the analysis of pedestrian moving on through railway station (*Daamen, 2004*).

4 PEDESTRIAN MOVEMENTS' ANALYSIS FOR DIFFERENT FACILITIES

4.1 Irregular pedestrian crossings analysis at traffic light zebra crossings – main behavior properties

The different nations punish the jaywalkers differently, when the pedestrian do not use the zebra or cross the signalized zebra crossing during red signal. In Singapore repeat offenders can be charged bigger punishment and a jail term. We see it many times that pedestrians do not use the zebra crossings or cross the zebra during red signal. A lot of things can influence these movements at the international research present, e.g. hurry life-mode, car-oriented traffic design, differences in the culture etc. It is not easy to decide which effect causes these irregular crossings. The pedestrians do not like waiting at traffic lights.

During my analysis I analyzed irregular pedestrians at traffic light, who did not wait for the green time. Those people are not in the sample that arrived during the green time. Between 2012 and 2014 I made video records on 15 places in Budapest in peak and out of peak periods as well. The records were 5-10-15 minutes long, it depends on the volume. During the analysis I would like to ask which parameter causes the irregular crossing. Can the reason be the pedestrians' delay, the length of the crossing or the crossed traffic volume? During an irregular crossing I measured the critical gap time (critical reach time[1]), with it I can present how these pedestrians take high risks.

4.2 Reviewing the pedestrians' green time at traffic light zebra crossings

In my dissertation I present the specifications and the previous standards as well as calculation green time at signalized zebra crossing. The national guidelines proposed the followings in terms of planning signalized pedestrian crossings (MAÚT, 2009): *assume an average speed of 1.34 m/s to determine the crossing time for pedestrians, to determine the shortest possible free signal assumes a speed of 1.0 m/s for the slowest pedestrian, who has to reach the 2/3 of the total crossing distance. In special cases pedestrians has to pass the halfway-line with a speed of 1.2 m/s.*

However, more studies show that the 1.2 m/s crossing design speed is higher than real life, if there are more disabled people (*Hoxie et. al, 1994*) (*Langlois et al., 1997*).

In practice the phase time plan is made based on the vehicle volumes, so the average pedestrian's waiting time depends on vehicle volumes. With the increase of vehicle volume the cycle time increase proportionately and the necessary vehicle's green time. Currently the design process is car traffic oriented. I measured the pedestrian free flow speed at signalized zebra crossings, which was the basis of the research short green time theory. I differentiated between the number of traffic lanes and the length of the crosswalk. I suggested renewing the calculation of pedestrian green time after the statistical evaluation based on the international literature.

[1] Definition: this interval, when the vehicle arrives to the conflict zone, after irregular pedestrian. This time is unfortunately lower than the stop distance. In ideal case the pedestrian left this conflict zone before the vehicle.

4.3 Verifications of the effective stairway width design

The capacity of the stairways is really different in the literature. In the first step I collected and looked through these capacity values and the methods. The capacity of the stairways is the following: ~2000 P/h/m (*Metró Tervezési Irányelv)* 2000 P/h/m, one direction upwards 2200 P/h/m). The dissertation contains the detailed data. The Hungarian specification suggests 6 LOS as *Fruin* for this facility. The previous standard (*GYATSZ)* recommends a calculation formula, with which the effective stairway width can be calculated. (It is important to put emphasis on the fact that is does not take the directions of the flow into account.)

The formula is the following:

$$SZ = \frac{F}{v * D},$$

where: SZ: effective stairway width (m),
F: peak volume (P/s),
v: design speed (m/s) 0.5 m/s,
D: design density (P/m^2) 1.4 P/m^2.

This speed is LOS C in Hungarian and American measurement method, while the design density is LOS D in Hungarian specifications and LOS E in *HCM*. The reviewing of the design method had to start with *in situ* measurements. Video records were made at these places as well. Two pedestrian groups were differentiated during evaluations: young, old people (good physical condition) and old people, adults with small children or with pram or physically disabled pedestrian. I made these records in peak and out of peak hours as well.

4.4 Zebra crossings use for two lane roads with and without refuge island

The zebra crossings are built at wider cross-sections with refuge island, at smaller width without middle island. In my opinion in most cases signalized crosswalks are built without reason. I present shortly the previous and current regulations in the dissertation. The current Hungarian specification gives recommendation for pedestrian crossing facility type solutions until 8.5 m width carriageway. The difference is that we can choose facility type based on three different speed categories (30, 50, 70 km/h). The designers have to reconsider in many cases. For example 1200 v/h total vehicle volume can be crossed with signalizing and with refuge island as well at 50 km/h speed. 300 P/h pedestrian volume (or higher) can be crossed only with signalized crossing at 50 km/h speed with 1200 V/h traffic volume. The regulation is the same as the German specification (*EFA, 2002*).

For the application of VISSIM microsimulation models the following measurement were done by the author. I analyzed the situation at zebra crossings for one and for two direction traffic volume. The pedestrian free flow speed was measured on three places in Budapest: Bertalan Lajos Str., Budafoki Str. and Etele Road. 60% of the pedestrians crossed the zebra at 1.5 m/s or slower (n=321, dev.=0.26 m/s). The minimal speed was 0.8 m/s, the maximum was 2.2 m/s.

I made VISSIM models after the *in situ* measurement. The software's advantages that for each traffic combinations can be checked the facility during the running. During the process I collected the time delays for pedestrian and for vehicles as well. My objective was to create a recommendation for homogenous traffic volume and for two-lane road, which can help the designers to choose among a traffic light, zebra crossing with and without refuge island.

4.5 Level of service analyses of tramline platforms

The crowded trams and tram stops in Budapest egg me to analyzing tramline platforms. In the dissertation the analyzed spaces and the result of the counting are presented. I show the different LOS categories on international level and most important definitions. After the introductions of an international (American - HCM) method other recommendation of manuals I suggest based on the counting new platform design method for Hungarian tram line platforms (effective width). I checked the LOS of the platforms with VISSIM software, and based on the simulation the widening is necessary.

The national tramline platform design (*ÚME, 2009* and *BKV, 2000)* suggests only a minimum width. The BKV Manual recommend 1.3-1.5 m width side platform (middle island platform min. 4 m), the ÚME suggest minimum 1.8-2 m width facility (middle island platform min. 3 m).

The tramline platform on Kálvin square is 5.6 m width; its length is 33 m. At the end of the platform a 4 m width stairway connected, through it the passenger can transfer to M3 underground[2]. Each ends there are signalized pedestrian crossings. The 70% of the passengers came /gone through the stairways. In peak hour the platform and the stairways are too crowded. The width of the platform is not enough. Based on the simulation and on the design method the ideal platform's width is over 7 meters.

On Szent Gellért Square the tram stop has two side platforms, which width is 3 m, length is 50 m. The effective width is smaller because there is safety barrier and a protection facility (weather, rain). The length of the vehicles is 26 m long, two vehicles cannot arrive to the stop at the same time. The overcrowded side platform's (direction to Pest) LOS is 'F'. The other side of the platform is LOS E, towards Buda in peak hour, based on the American design method.

The LOS is influenced by the signalized zebra crossings because after the arrival of a tram the traffic light does not change to green immediately. The ratio of the irregular pedestrians crossing is too high.

4.6 The effects of the pedestrian volumes for the right turn lane's capacity at signalized intersection

The right-turn lane's capacity decreases if the phase is the same and if the pedestrian volume increases at signalized intersections. The ÚME gives the saturated volumes for lanes (direct, direct-right and right turn), which can be used if the planners do not have any data. The capacity of these lanes are given in function of the curb radius and in function of pedestrian volume.

[2] During the counting the M3 metro operated only (October in 2013)

The ÚME describes the limit of the pedestrian volume: no pedestrian volume, low, middle or high pedestrian volume. It does not give numerical value of its. The capacity's decreasing in function of pedestrian volume can stand up with the *in situ* measurement and the microsimulation analyses.

The analyzed Kálvin circus is a complicated junction with public transport, cycle flow and with huge vehicle traffic. The right turn lane for Üllő Road from Vámház Ringroads was chosen for analyzing based on these respects. The geometric and the traffic light program are the same in the simulation as the real life. There are no previous measurement data, so the calculated right turn lane capacity is stand up with the ÚME specification. The calculated right turn lane capacity (if there is green sign) is 167 pc/h/lane. The same phase's capacity with parallel pedestrians crossed flow is 115 pc/h/lane. The difference is -52 pc/h/lane.

5 NEW SCIENTIFIC RESULTS

As a summary of this work the main new results and conclusions are reported in the form of 6 theses:

Thesis 1
Irregular pedestrian crossings analysis at signalized zebra crossings

I verified with measurements that the reason of the irregular pedestrian crossing is not the suffered loss of time or the length of the zebra crossing. However there is a logarithmical function relation between the ratio of the irregular pedestrian crossing and the crossed vehicle volume (semi closed connection).

I can determine based on the measurement at signalized pedestrian crossings, that the 87% of irregular cross walkers crossed the zebra after the last vehicle. I presented with critical gap time that these pedestrians take a high risk.

I analyzed the irregular movements at signalized crossings. (I calculated and evaluated the recorded video.) I also tried to find correlation among the irregular crossing, the lost time during the crossing and the length of the crossing. By measuring the headway of the irregular crossings and the vehicles I concluded that the pedestrians take a high risk.

The gap when the pedestrians still start crossing is really short, 2-3 seconds. 87% of the pedestrians crossed the zebra after the last vehicle (which travels in column). Based on measurements I verified that the average walking speed of irregular pedestrians are higher to 8 % as the regulars.

The average time delay does not egg the irregular pedestrian to cross the zebra. However there is a logarithmical function relation between the ratio of the irregular pedestrian crossing and the crossed vehicle volume (semi closed connection) ($R^2 > 0,5$). My next hypothesis was the following: the length of the zebra crossings eggs these pedestrians to cross irregular if it is shorter. Between the ratio of the irregular pedestrian cross walkers and the length of the zebra there is no function relation ($R^2 < 0,3$).

The results of the two tests are that more men in proportion cross the road irregular than regular and the female are in compliance with the law.

During my research I fund two solutions for decreasing the irregular crossing which can operate well in Hungary as well. The Vienna's and Graz's solution can be a good practice in Budapest when the traffic light changed immediately to green after the tram arrived at the tram stop. The other solution is that only a sign on the carriageway (tram trucks) [Attention tram!]. There are a lot of tram stops where the traffic lights do not operate through the tracks between the refuge islands in Frankfurt am Main yet.

Publications: [5] [7]

Thesis 2
Reviewing the pedestrian's design speed at signalized zebra crossings

I verified based on my measurements that the pedestrians design walking speed is overestimate at signalized zebra crossings. I suggested 0.75 m/s design speed for the lowest pedestrians'.

I determine based on my measurements results that the $s_{50\%}$ and $s_{15\%}$ of pedestrian's speed increases with the number of traffic lanes. Between these speeds and the number of traffic lanes there is linear function. I demonstrated a close connection (R^2=0,84 and R^2=0,92).

I compared my data with previous measurements and I determined that the $s_{50\%}$ pedestrians' speed increased to 10% in the last 30 years.

The older/slower pedestrians usually cannot reach the 2/3 of the whole zebra crossings; the clear green time is not enough in these cases. The ratio of the elderly and disabled pedestrians are higher in non-peak hours, they are not negligible if the number of crossed lanes are more than two. If there is a refuge island for faster pedestrians, a one-phase crossing with s50% has to be designed for them. My suggested pedestrian design speed can be used during the green time and the clearance (lost) time calculation.

Publications: [12] [7] [1] [14]

Thesis 3
Design recommendation for public stairways' effective width

I compared my results on crowded stairways with previous measurement data, and I suggested a new design speed based on the national and international methods for category I. and for category II. stairways. I reconsidered the Hungarian design method after the detail volume counting and pedestrian speed analysis. Based on these analysis I suggested using the following design speeds (v25%=0.65 m/s) in this previous formula.

The formula is the following:

$$SZ = \frac{F}{v * D},$$

where: SZ: effective stairway width (m),

F: peak volume (P/s),

v: design speed (m/s) $v_{25\%} = 0.65\ m/s$,

D: design density (P/m^2) cat. I. $0.55\ P/m^2$, cat. II. $0.75\ P/m^2$.

I determine that the speed's range upstairs is narrower at group of slower pedestrians based on detailed speed analysis on stairways (the elderly, the disabled people etc.). In peak hours the ratio of these pedestrians groups is low (fewer than 5%).

The currently designed method is not suitable for peak hours, it is necessary to analyze peak-5 min and peak-2 min volumes in some cases.

The previous design methods had two design categories. I suggested using these two categories (I. and II.) but with renewed design speed. The cat. I. stairways are built for high volume near the crowded public transport stops with LOS B. cat. II. is suggested to build with LOS C for lower volume, where the peak hour flow has a normal distribution. It is important to say that the result of the formula gives the effective width of stairways.

Publications: [12] [14]

Thesis 4
New methods for pedestrian crossing facilities design through two lanes

The method which recommend pedestrian crossing facility for two-lane roads (separated pedestrian crossings) assumes 50% yielding percent and 50 km/h average vehicle speed.

The refuge island has a positive effect on the pedestrian and on the vehicles based on the microsimulations, too. The time delay increases with the vehicle volume exponentially.

I suggest implementing the following results into the Hungarian specifications based on HCM's delay based Level of Service categories:

- **Till 600 P/hr pedestrian volume and under 1200 pc/hr vehicle volume the zebra crossing is enough without refuge island, if the vehicle flow is homogenous and the average speed is 50 km/h.**
- **Between 1100 and 1600 pc/hr (1600 pc/hr volume was set as the highest volume in the simulations) can use zebra crossings with refuge island. In the further research zebra crossings with traffic light will be analyzed.**

The signalized zebra crossing building is not reasonable for two-lane roads in every case.

I made two microsimulation models (with and without refuge island) for one and two direction traffic volume roads with different yield percent (50% of the drives give yield to the pedestrians in the models). I made runnings for different vehicles and pedestrian's traffic volumes (but the traffic volume is homogenous). I compared the average and maximum users' time delay, and with national and international results from literature. The trends of the functions are the same. The reason of the differences can be the different yield percent.

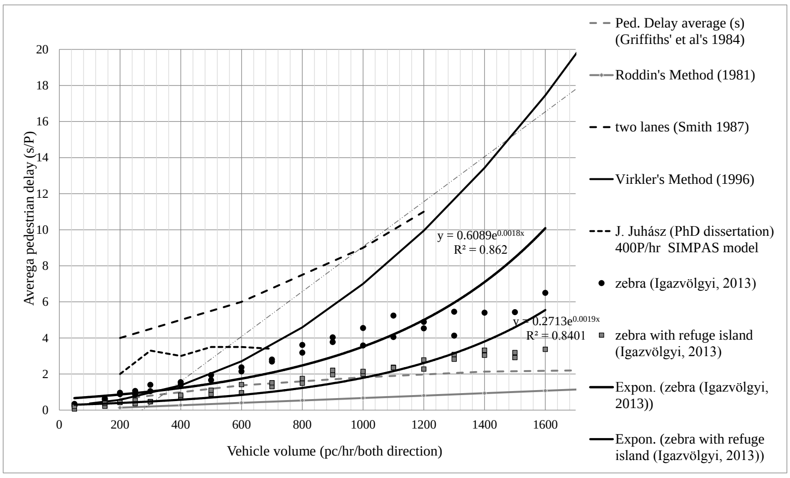

Figure 1 Average pedestrian delay- comparing with different method

It is important to take notice of the pedestrians' and the vehicles' time delay. The LOS categories come from HCM. It is needed to set the conditions (stop distance, sign of the crossings, and sign of the zebra crossings).

Publications: [3] [4]

Thesis 5

Level of service design method recommendation in Hungary for tramline platform effective width

I proved by measurements on location and microsimulation examination that the LOS of several tramline platforms is not satisfactory. I created a measurement method to the different LOS. The base of it was my own measurement. During the measurement, at least a LOS C has to be guaranteed. The six categories are the following:

Level of Service LOS	Design density D [P/m^2]	Description of the categories
A	=< 0.15	Free moving, free waiting
B	0.15 < D =< 0.3	Conflict free pedestrian transfer
C	**0.3 < D =< 0.45**	**Almost conflict free pedestrian transfer**
D	0.45 < D =< 0.6	The waiting space not enough, but the passengers wait on the effect length, the passenger change are slower
E	0.6 < D =< 0.75	Crowded platform, the passenger change is difficult
F	0.75 <D	Overcrowded, the passenger cannot wait on effective length, there are conflict during the passengers change

Tabel 1. Suggested LOS categories for tramline platform design

The measurement formula is the following:

$$SZ_e = \frac{\frac{F}{D}}{H_e},$$

where: SZ_e= the effective width of the platform (min and max) [m],

F= the number of waiting passengers at the arrival of the vehicle (P)

D= density at the given LOS (min, max) [P/m^2],

H_e= the effective length of the platform [m] (the length of the vehicle extended by 4 meters).

In order to determine the principles, I made passenger counting on several location in Budapest (alighting, boarding and waiting etc.) I concluded that the level of service is not satisfactory at these platforms. On the basis of the microsimulation, I verified that the waiting passengers do not wait permanently on the platform. They concentrated near to the doors. The connected facility (stairway, walkway) influenced significantly the platform's Level of Service.

On the basis of the examinations, I suggest introducing 6 Level of Services to national application. The "F" level is at Szent Gellért Square which means 54 passengers at the effective platform length (where no other passenger could wait near the vehicle). Taking into account the rush-hour traffic I recommend introducing density counting to check the appropriateness of the platforms. Moreover, I also suggest introducing new Level of Services.

Publications: [13] [6] [14]

Thesis 6

The right turn lane capacity measurement in function of crossings pedestrian volume at signalized intersection

I verified and determined the right turn lane capacity, which is ~1830 pc/h/lane. The capacity decreases logarithmically if the pedestrian volume increases. Based on the pedestrian volume I suggested 3 categories for the capacity decreasing:

- **small pedestrian volume: 0-10 P/min/two direction (right turn capacity decreases for 10%)**
- **medium pedestrian volume: 10-20 P/min/two direction (right turn capacity decreases for 10-40%)**
- **high pedestrian volume: 20 P/min/two direction (right turn capacity decreases for 40%)**

The right-turn lane's capacity decreases if the phase is the same and if the pedestrian volume increases at signalized intersections. Based on the analysis I determined that there is a relation between the pedestrian volume and the right turn volume. The differences between the measured and the calculated right turn lane capacity are significant.

Publication: [9]

6 THE UTILIZATION OF THE RESULTS AND FURTHER RESEARCH

The safety of the pedestrian connections and the level of service can be increased based on my results. For the tramline platforms there is no design method.

The analysis shows that the pedestrian volume causes traffic jam, and the value of the capacity decrease can be significant during the same phase at signalized intersections (pedestrians and right turn volume). My results can be used in the future for same signalized intersection's capacity calculations.

With the new design walking speed the safety-feeling of the pedestrians will increase. But it is important to know that the longer green time causes higher capacity increase. The analysis of the irregular pedestrians at signalized intersection can be useful for safety campaigns. At these campaigns the group of the gender and the elderly is important.

On two lanes roads separated zebra crossings can be operated well without traffic light. The delays of the users are lower at refuge island and zebra crossing.

There are further research utilities in the elevation differences at underground and at overpass. If these facilities are needed the designers have to plan other facilities (elevator, ramp) to help disabled pedestrians. In Hungary it is not necessary to construct between 3 and 7 meters deep elevation differences moving stair. The comfort can be increased at M3 metro stations in Budapest, where there are side platforms, and to reach the other platforms, the passenger has to get 'through' the tunnels (Árpád Bridge station, Gyöngyösi Roads station).

In the future I will analyze different possibilities on platforms and on waiting area, e.g. signalized waiting area, where the vehicle's doors will be after the arrival. These solutions are used in other countries, with which the number of crowded situation can decrease during the alighting and boarding process. Passengers waiting's space problem can be seen in bus stops as well. In further research I will analyze the effects of obstacles on platforms and on waiting areas. These obstacles and safety barriers (at side platforms) have an extra 'dead space'.

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