Simulation of the Influence of Increased Speed Limit and Densification of Stations on Travel Time Based on the Example of the First Metro Line in Warsaw

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Abstract—**The author's original model for travel time of metro trains is presented in this paper. The presented model is assumed to be an instrument for estimation of reliable travel times of metro trains in macro simulation models of whole transport networks. These kinds of models are used to evaluate the effects of the possible implementation of major transport investments in cities. The quality of the network model can significantly affect the results of analyses, and even the selection of optimal solutions. Travel time is the basis for every transport network model, not only for the current state, but also for the future. This is particularly important in the case of planned sections, where one cannot use measurement results. Partial models of metro average running times and random components of running time, depending on the length of sections, were created on the basis of the results of measurements carried out for the first metro line in Warsaw. Also, the dwell time at stations is included into the model based on the results of measurements made for three separate station types, diversified on the basis of average stopping times and location of the station in relation to the inner city centre. The paper includes examples of practical model application: evaluation of the influence of increasing the allowable speed, and densification of the stations on travel time and also the impact of the accuracy of the travel time model on simulation results of passenger flows.**

Keywords-metro; traffic simulation; travel time.

I. INTRODUCTION

The metro is commonly perceived as one of the best urban transport systems, as it enables fast transportation of passengers. Its utility increases appropriately to the distance of a trip. This is the effect of consequent separation of the entire track, and long distances between stations, which allows high speed train, up to 60 [km/h] or more. This results in high transportation speeds (compared and summarised by Feng at al. [6]), of around 35-40 [km/h]. The metro is also associated with a large transport capacity [13] [17], as well as high operational reliability [3]. However, high speed does not go hand in hand with accessibility. Long distances between stations lead to long walking distances to find a station. These issues have been discussed by García-Palomares at al. [7]. For this reason, a metro does not perform well in high density areas. Significant investment and operating costs are another downside of the metro.

The aforementioned pros and cons create the necessity to perform a thorough analysis of costs and benefits before the potential introduction or expansion of a metro system. Discussions as to, whether it is legitimate to build (or extend) a metro line are usually a consequence of the insufficient utility of existing systems of urban public transport. Very often, this is a common effect of a lack of determination and a consequence of giving priority to over-ground means of public transport. Arguments used in these discussions are very different, but always one of them is high travel speed of metro trains.

Discrepancies between expected and possible travel times, appear as early as during the planning stage. Meanwhile, travel time has a crucial influence on modal split, especially considering rail and tramway systems that are able to transport the greatest passenger volumes. Even slight differences in travel time may have a considerable influence on increased or decreased passenger volumes, not only on the metro line itself, but also on other lines of public transport. These differences also result in changes in car volumes.

Therefore, travel time is an obligatory element of a four-stages procedure (described, among others, by Hensher [9]), commonly used in the planning of transportation systems. Reliable estimation of transportation speed for individual variants of metro line routes is obligatory for a determination of potential effects of differentiated variants of transport investments. Only such an approach allows a reliable determination of outcomes of serious transport investments.

To provide a fully reliable basis for the potential construction of a metro line, it is necessary to describe processes of train movement in greater detail. It is thus essential to possess precise knowledge of both current and achievable realistic running times and times spent by trains at the stations.

This paper presents a general travel time model for a metro line that may be used for planning such investments in various cities. The main purpose of the analysis was to recognise the mechanism of changes in travel time of metro trains and to build a model that would serve to estimate the length and variability of travel time. Section 2 presents a general model of travel time for a metro line, whilst in Section 3 there is a description of measurement' results from the first metro line in Warsaw. Sections 4 and 5 explain the results of estimations of running time and dwell time at the

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stations. In Section 7, examples of possible simulation results are shown. Finally, Section 8 presents the conclusion of the paper.

II. General model of travel time for a metro line

A. Structure of the model of travel time for a metro line

The graph theory [8] allows the assumption that consecutive stations are vertices of a directed graph and the sections between the stations are directed edges. From the point of view of a general structure, the model of travel time for a metro line will not differ from travel time models for other means of transport, e.g., trams or buses, described for instance by Vuchic [12] and Bauer [2].

However, there are certain differences at the stage of modelling events specific to a metro line. In models of bus or tram lines, the registered events are: arrivals and departures at stops, moments of starting and ending the process of passenger alighting and boarding, as well as the moments of standstill at any given point within the network, such as crossroads or pedestrian crossings. In a model of a metro line, the number of occurrences may be significantly limited [4]. The fully separated route of a metro line and the full (or at least very advanced) automation of train rides decrease the need to consider any events between stations. Of course, such events may happen (mostly for security and safety reasons), but they are relatively rare. In turn, automated processes of simultaneous opening or closing of train doors question the division of the dwell time into separated processes (alighting and boarding, time of waiting for possibility to departure). As a result, only two types of events on the line have been accounted for in the presented model:

- the moment when a train is brought to a halt upon arrival in a station (defined as the moment of starting of opening the door);
- the moment when the train leaves the station (the same as moment of starting of closing the door).

Thus, it may be acknowledged that the structure of the travel time model for a metro line will comprise a group of modules: section between stations - station at the end of section. Only two processes of movement will be considered:

- running time – counted from the moment of departure from a station until arrival at the next station;
- dwell time – time spent at a station, counted from the moment of arrival to the moment of departure.

The analysis omitted time spent at the first and last station, as these do not have any direct influence on train travel time and the duration of passengers' trips.

B. Mathematic structure of the model of travel time for a metro line

The mathematical structure of the proposed model strictly corresponds to its approved general structure. In general, travel time for trains within a metro line is the sum of travel times for sections between stations and the time spent at the stations [1]:

$$T = \sum_{m=1}^{p} t_{r,m} + \sum_{m=1}^{p-1} t_{s,m} \tag{1}$$

where:
T – travel time for the whole metro line (one direction) [s];
$t_{r,m}$ – running time for an individual section between stations (v_{m-1}, v_m) [s];
$t_{s,m}$ – dwell time - time spent during a halt in a station m [s].

According to the deterministic approach currently used to solve most practical problems, average travel time for a line may be presented as the sum of average values of travel time and dwell time:

$$\overline{T} = \sum_{m=1}^{p} \bar{t}_{r,m} + \sum_{m=1}^{p-1} \bar{t}_{s,m} \tag{2}$$

However, in more detailed analyses it is desirable not only to decrease average travel time, but also to decrease dispersion of travel times for a line. This justifies the consideration of additional random components of running time and dwell time. It is thus reasonable to expand the formula (1) by random components, as presented:

$$\widetilde{T} = \sum_{m=1}^{p} \left(\bar{t}_{r,m} + \hat{t}_{r,m}\right) + \sum_{m=1}^{p-1} \left(\bar{t}_{s,m} + \hat{t}_{s,m}\right) \tag{3}$$

The ability to estimate travel time dispersion increases the quality of the model and spreads the scope of its uses such a model can also be used in dynamic modelling. Taking well-adjusted random components of the model, one can calculate the influence of travel time variability on passenger volumes.

III. First line of the Warsaw metro

A. Description of the metro line

Estimation of travel times for sections between stations and dwell time at the stations were based on results of automatic traffic measurements on the first metro line in Warsaw. The line is 21.648 [km] long (one direction) with 21 train stations. Distances between stations [18] vary from 0.577 to 1.534 [km], with an average distance of 1.082 [km]. The line constitutes a vital element of the track-based urban transportation system of Warsaw. For this reason, it has been decided to build a second metro line in the East – West direction [16].

According to [15], an estimated 147.2 million passengers used the Warsaw metro in 2013. Metro trains covered a total of 23.8 thousand [train-km] during this period.

B. Transportation speed

The calculations used measurement results made available by the Public Transport Authority for Warsaw. The results are from two average working days (19.11.2013 and 16.01.2014, when no serious traffic disturbances were observed). The analysis encompassed 581 train journeys (in the direction “Kabaty” – “Młociny”) and 591 train journeys (in the direction: “Młociny” – “Kabaty”) that occurred between 4 AM and 12 PM. Even though the results used concerned 2 days only, they have been acknowledged as being representative for an average working day on the Warsaw metro. Transportation speeds on the first metro line are considerably high, with a daily average of 35.9 [km/h] (direction: “Kabaty” – “Młociny”) and 35.4 [km/h] (direction: “Młociny” – “Kabaty”). This does not mean that the transportation speeds are fixed. On the contrary, differences between speeds in the following hours of the analysis may be significant, as illustrated in Figure 1.

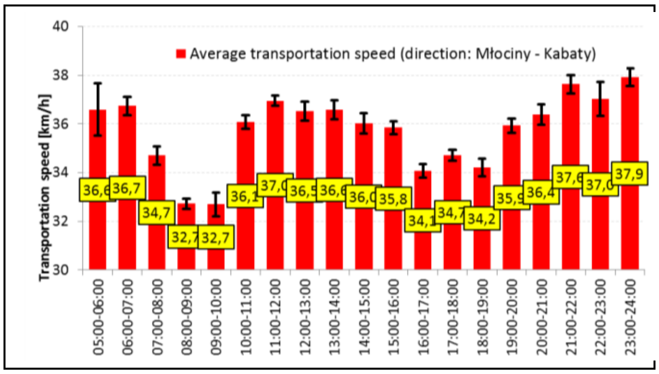

Figure 1. Variability of transportation speeds on the first metro line (direction: Młociny - Kabaty) within the hours of the line operation.

This figure shows the scale of standard errors connected with estimation of average transport speeds. In travel time modelling, it is vital to reproduce traffic conditions within a given time of day. Dispersion of transportation speeds occurs even on metro lines. Thus, it has been suggested to divide a working day into six time periods, differing mostly in term of current train frequency in the first metro line in Warsaw:

- **early morning** – train departures within the hours: 04:00 AM - 5:59 AM, estimated scheduled interval on the line: 4-7 [min];
- **morning** – departures: 6:00 AM - 8:59 AM, interval: 3 [min];
- **late morning and early afternoon** – departures: 9:00 AM - 02:59 AM, interval: 4 [min];
- **afternoon** – departures: 03:00 PM - 06:59 PM, interval: 3 [min];
- **early evening** – departures: 07:00 PM - 08:59 PM, interval: 4-7 [min];
- **evening** – departures: 09:00 PM - 11:59 PM, interval: 9-10 [min].

Usually, models of transport networks are built for the morning or afternoon peak hours, when most journeys happen. On the first metro line, average travel time during the afternoon peak is 37.5 [min] (difference between average travel times in both directions is only 3 [s]). This means that during this period, transportation speed equals 34.7 [km/h].

Models for other time periods can also be created. It is most important to adjust the model of travel time on the metro line to the models of travel time of other means of transport, so as to ensure realistic effects in terms of passenger flow between the various means of transport. That is why the aforementioned division of the working day into time periods has been proposed. Relatively speaking, the highest values of average transportation speed were reached within the hours between peaks, in early evening and evening hours - above 36 [km/h]. Lowest average transportation speeds were reached during single hours of the morning peak, between 08:00 AM and 09:00 AM and from 09:00 AM to 10:00 AM (direction: “Młociny” – “Kabaty”) and the afternoon peak, from 05:00 PM to 06:00 PM (second direction). Within the aforementioned hours, average transport speeds fluctuated around 33 [km/h].

Variability of transportation speeds within a single hour was highest in the morning and evening periods. This may be caused by the lower number of train courses and greater size diversification of passenger flow. The results confirm the fact that, despite the total separation of the metro system from other means of transport within the traffic system, variability in transportation speeds occurs and it is worthwhile considering the reasons for this.

C. *Travel time structure of the first metro line*

The search for the reasons for dispersed travel times of metro trains began with a division into running times between stations and dwell times. This allowed the determination of which element of the metro line was more susceptible to disturbances. The ratio of the total sum of running times to whole travel time is 67.5 [%] (direction: “Kabaty” – “Młociny”) and 68.3 [%] (“Młociny” – “Kabaty”). This means that an average of 1/3 total travel time for the entire line is spent at stations. This ratio changes from 67.5 [%] in the afternoon (direction: “Kabaty – Młociny”) up to as much as 72.8 [%] in the evening (“Młociny – Kabaty”).

D. *Comparison of changes in time of ride between stations and time spent during halts in the stations*

The longest travel times for the metro line have been observed in the morning and afternoon periods. In general, slightly greater differences have been observed in the direction “Młociny” – “Kabaty”, as average travel time in the early evening is 3.0 [min] shorter than the corresponding time in the morning (Figure 2).

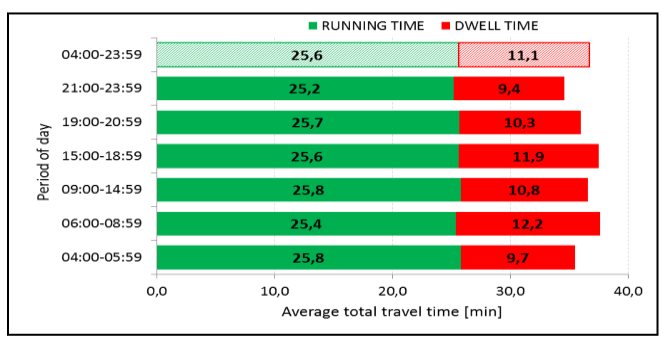

Figure 2. Variability of totall travel time divided into running time between stations and dwell time (direction: “Młociny” – “Kabaty”).

In the other direction, the difference is 2.7 [min] – between the early evening period, when travel time is shortest, and the afternoon period of the day. It may also be observed, that differences in running times are significantly smaller than differences between dwell times. This fact will be taken into account during model component estimation.

IV. Estimation of Travel Time for a Section between Stations

A. Average running time

Running time between stations - in the case of a metro system - is affected by considerably fewer factors than in the case of over-ground systems of urban public transport. Stop-to-stop sections on the metro line are fully separated, the most crucial factor affecting the travel time is section length. Far less important are geometrical factors such as horizontal curves or longitudinal grades. Possible travel time disturbances usually result from the necessity to counteract atypical situations. For example, longer dwell time of preceding train leads to slowing down or even stopping the upcoming trains between the stations. Differences in running time can also be caused by dispatching tactics, especially in the case of a high frequency of trains. These influences were described by Yang at al. [14] and also by O. Yalçınkaya and G.M. Bayhan [13]. Important is also the condition of a track system and the kind of power system.

First, the estimation of the average running time for a section between stations was carried out. The aim was to check how the length of a section influences the running time and, if a satisfactory model was not obtained, other factors were taken into consideration. The metro has an automatic system control, so a physical model, based on calculations of acceleration and deceleration times and running time with constant speed, can be used:

$$t_r = \frac{L}{v_{\max}} + \frac{v_{\max}}{2}\left(\frac{1}{a} + \frac{1}{b}\right) \quad (4)$$

where:
t_r – average travel time for a section between stations [s];
L – length of a section between stations [km];
v_{max} – maximum speed on the section [m/s];
a – average acceleration rate[m/s^2];
b – average deceleration rate[m/s^2].

After preliminary application of the model, it transpired that the differences between the measurement results and the calculated results were relatively large - a total of nearly one minute in one direction. Therefore, a statistical, regression model was sought, which would give a better fit to the measurement results and, additionally, be more versatile and able to take into account random influences. For this reason, the linear and non-linear regression methods were used.

In the case of four out of the six periods of a working day, the best adjustment of the model of average running time to the results of measurements carried out for the first metro line in Warsaw was obtained through the use of the double-squared model:

$$\bar{t}_r = \sqrt{(\beta_0 + \beta_L \cdot L^2)} \quad (5)$$

where:
t_r – average travel time for a section between stations [s];
L – length of a section between stations [km];
β_0, β_1 – simple regression parameters [-].

In the two remaining cases, other models offered a slightly better fit (1-2 [%] higher values of determination coefficients). Eventually, it was decided to use the double-squared model for all the periods of a day. Figure 3 shows the effects of fitting the model to the measurement results.

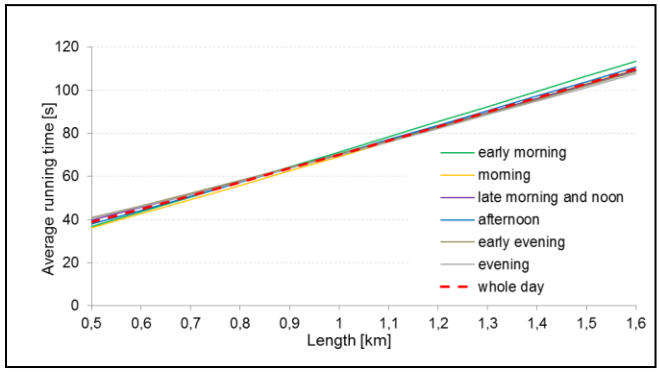

Figure 3. Models of average running time dependent on section length, for acknowledged periods of a working day.

Comparing models for particular periods of a working day, it may be noticed that there are only slight differences in the obtained average travel times. For example, for a section of 0.7 [km] the maximum difference equals just 3 [s] – running time in the morning equals 49 [s], while around noon, in the afternoon and in the early evening it amounts to 52 [s]. For a section of 1.5 [km], average running times differ by 6 [s] – from 101 [s] in the evening to 107 [s], early in the morning. Such a small variability of average running times encouraged the search for a single universal formula for the whole working day. This has the following form:

$$\bar{t}_r = \sqrt{(363 + 4564 \cdot L^2)} \quad (6)$$

This dependence is characterised by a high value for the determination coefficient, amounting to 98 [%]. This means that the length of a section between stations can be considered as the only crucial factor influencing the average travel time on this section, regardless of the period of the working day. It also means that the frequency of train runs even as high as 20 trains per hour does not influence the average travel time on the section.

This model of average running time can be easily used during the construction or actualisation of the Warsaw simulation transportation model. With a couple of additional assumptions, it can also be useful in the transportation models of other Polish cities, where maximum running speed of trains will be 60 [km/h].

Conversion factors that may be applicable in the case of modelling higher maximum running speeds were also calculated. It was established that only the section length on the metro line has a crucial meaning for running speed. In this calculation (because of a lack of data), physical dependences were used. Maximum running speeds of 70, 80 and 90 [km/h] were taken into consideration. In all three cases, one can use the regression formula:

$$k = \sqrt{\eta_0 + \frac{\eta_1}{L}} \tag{7}$$

where:
k – conversion factor [-];
L – length of a section between stations [km];
γ_0, γ_1 – regression parameters [-].

Values of regression parameters for equation (7) are shown in table I.

TABLE I. REGRESSION PARAMETERS FOR RECALCULATION OF RUNNING TIMES

Regression parameters [-] for different increase of speed					
60 -> 70 [km/h]		60 -> 80 [km/h]		60 -> 90 [km/h]	
γ_0	γ_1	γ_0	γ_1	γ_0	γ_1
0.756	79.9	0.593	143.4	0.477	197.9

B. Random component of running time

In the case of micro-simulation models, there is a possibility of considering the randomness of travel time. Then, it becomes necessary to generate random travel time coefficients for particular sections. These can be simulated by a random number generator from normal distribution with mean zero and standard deviation specified on the basis of measurement results (in [s]):

$$\hat{t}_r = N[0; \sigma_r] \tag{8}$$

Values for standard deviations of the running time can be determined as a function of a section's length. The best fit of the model to the measurement results is as follows:

$$\sigma_r = e^{(\gamma_0 + \gamma_L \cdot L^2)} \tag{9}$$

where:
σ_r - standard deviation of running time for a section between stations [s];
L – length of a section between stations [km];
γ_0, γ_1 – regression parameters [-].

Initially, partial models were constructed for all of the six periods of a working day (Figure 4).

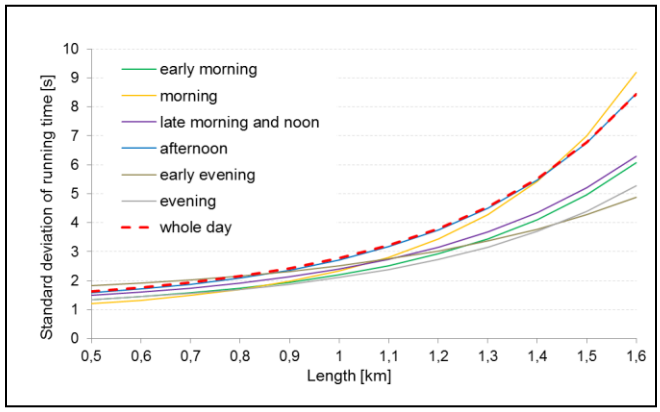

Figure 4. Models of standard deviation of running time dependent on section length, for acknowledged periods of a working day.

However, standard deviations of running time, obtained thanks to the models, differ very little from one another. For sections of lengths up to 1.2 [km], the difference amounts to a maximum of 1 [s], while in the case of a section of 1.6 [km] – only 4 [s]. This is why only one formula was chosen, and this describes the relation between the standard deviation of a running time and the section's length. The formula is representative for a whole working day:

$$\sigma_r = e^{(0{,}310 + 0{,}712 L^2)} \tag{10}$$

The model above is not characterised by a high value for the determination coefficient, as it is in the case of the model for the average value – R^2 amounts to only 48 [%]. However, taking into consideration the fact that in the case of the first Warsaw metro line the standard deviations are an order of magnitude smaller than average values – the model can be considered satisfactory, thus it can be recommended to be used in micro-simulation analyses.

V. ESTIMATION OF DWELL TIME OF A METRO TRAIN

A. Average dwell time

The dwell time has a more individualised character. It depends mainly on the size of flow of alighting and boarding passengers, and on the number of passengers already travelling on a train arriving at a station. In the case of new investments, the flows are determined at the stage of network planning. It is necessary to determine preliminary dwell times, which may be later verified by an iterative procedure. Since at the stage of carrying out the analyses, reliable sizes of passenger flows for the first line of Warsaw metro were not available, it was decided to differentiate the stations on the basis of the average dwell time. Interestingly, the dependence between the length of dwell time and the location of the station relative to the inner centre of the city was observed. On this basis, 3 types of stations were defined:

- Type A – stations located in the inner city centre (in the case of the first line of the Warsaw metro – four

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stations in both directions: “Ratusz Arsenał”, “Świętokrzyska”, “Centrum” and “Politechnika”);
- Type B – stations located within the urban area (“Plac Wilsona”, “Dworzec Gdański”, “Pole Mokotowskie”, “Racławicka”, “Wierzbno” and Wilanowska);
- Type C – stations located in the remaining areas of the city (remaining stations on the first metro line).

Table II shows the breakdown of average values of dwell times at station types A, B and C.

TABLE II. AVERAGE VALUES OF DWELL TIME DEPENDENT FROM THE LOCATION OF THE STATION RELATIVE TO THE INNER CENTRE

Type of station	**Average dwell time [s]**						
	Early morning	**Morning**	**Late morning and noon**	**After-noon**	**Early evening**	**Evening**	***Whole day***
A	36	**47**	39	**50**	38	34	*43*
B	31	**38**	34	**39**	33	31	*36*
C	28	**32**	31	**32**	30	29	*31*
All stops	*31*	***37***	*34*	***38***	*33*	*30*	*35*

It can be seen that the values of average dwell time vary significantly during the day. This variability should be taken into account in macro-simulation models performed for peak periods. In a more specific approach, average dwell time can also be estimated more precisely as a function of numbers of alighting and boarding passengers – if this kind of data is available.

B. *Random component of dwell time*

Dwell time generally has a Normal distribution, which is confirmed by the Chi-square statistical test. Therefore, the random components of dwell times (in seconds) can be determined from the Normal distribution of zero mean value:

$$\hat{t}_s = N[0;\sigma_s] \tag{11}$$

Standard deviations were calculated for three specified types of stations: A, B and C (Table III).

TABLE III. DWELL TIME STANDARD DEVIATIONS DEPENDENT FROM THE LOCATION OF THE STATION RELATIVE TO THE INNER CENTRE

Type of station	**Standard deviation of dwell time [s]**						
	Early morning	**Morning**	**Late morning and noon**	**After-noon**	**Early evening**	**Evening**	***Whole day***
A	4	**12**	6	**11**	6	4	*7*
B	4	**5**	3	**6**	4	3	*4*
C	1	**2**	2	**3**	3	2	*2*
All stops	*4*	***8***	*4*	***9***	*5*	*3*	*6*

A much greater diversity of standard deviations for dwell time can be seen than in the case of running time. This is due to the fact that the number of alighting and boarding passengers is very random.

VI. EXAMPLES OF THE MODEL IMPLEMENTATION

A. *Considered scenarios*

Implementation of the metro line travel time model has been shown on the basis of the analysis of possibility of densification of Warsaw’s first metro line stations and led to the announcement of raising the maximum speed to 80 [km/h]. The first one is associated with a lengthening of running time, the second with its shortening. The following scenarios are considered:

- **Scenario S0**: existing state of first metro line;
- **Scenario S1**: two additional metro stations (both directions): station “Plac Konstytucji” (Type A, between existing stations: “Politechnika” and “Centrum”) and station “Muranów” (Type B, between stations: “Ratusz Arsenał” and “Dworzec Gdański”) and changing the type of the station “Ratusz Arsenał” from A to B;
- **Scenario S2**: increasing the maximum speed of trains from 60 to 80 [km/h];
- **Scenario S3**: two additional metro stations: “Plac Konstytucji” (Type A) and “Muranów” (Type B), changing the type of the station “Ratusz Arsenał” from A to B, and additionally increasing the maximum speed of trains from 60 to 80 [km/h].

In this calculation, only average metro trains travel times in afternoon period were calculated. Additionally, it was stated that passengers streams were constant, and dwell times would be the same. An extended analysis should take into account the influence of growth of passenger streams because of station densification in the city centre and growth of running speeds on the sections.

B. *Comparison of travel times*

The model was positively verified. In both directions, there are only 12 [s] differences between total travel time from the model and from the measurements. This means that the model can be used to calculate the effect of increasing the running speed and implementation of new stations.

The final results of the calculations of travel times are presented in Table IV. Introduction of two additional stations will result in lengthening of the average travel time by 1.4 [min], which will lead to a decrease in the average transportation speed from 34.9 to 33.5 [km/h]. However, increasing the running speed from 60 to 80 [km/h] can compensate for this inconvenience. After scenario S3 implementation, total travel time decreases to 35.2 [min] in comparison to the current state, which is a very satisfying value. More precise effects can be specified thanks to the iteration procedure (macro-simulation analysis), where the above values should be used as initial values. Only a multi-criteria analysis will allow full assessment of the options, e.g., via the method described by Nosal and Solecka [10].

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TABLE IV. COMPARISON OF TRAVEL TIMES

Parameter of the metro line	Scenario			
	S0	S1	S2	S3
Total running time [min] (all sections)	25.23	25.41	21.49	21.84
Total dwell time [min] (all stations)	12.03	13.33	12.03	13.33
Total travel time [min]	**37.26**	**38.74**	**33.52**	**35.17**
Share of total running time in total travel time [-]	0.677	0.656	0.641	0.621
Transportation speed [km/h]	**34.9**	**33.5**	**38.7**	**36.9**
Change of transportation speed, in relation to S0 [%]	*	**4.0**	**-10.9**	**-5.7**

C. *The effects of travel time model in the simulation of the entire transport network of Warsaw*

Comparisons were made for passenger flows for the scenario S3 using the simulation model of the Warsaw transport network. To estimate the travel time of metro trains, a common approach of constant running speed was used, together with a proposed approach: a model of travel time, which takes into account the variability of travel time. The calculations were performed for the years 2016 and 2036. The results are shown in Table V.

TABLE V. COMPARISON OF PASSENGER STREAMS – S3

Parameter of the metro line	Constant running speeds		Speeds from the presented model	
	2016	2036	2016	2036
Number of metro passengers	53 877	61 745	54 119	62 189
Number of all public transport passengers [persons/h]	321 952	406 817	322 312	407 287
Total number of passengers (public and private transport) [persons/h]	418 610	542 083	418 610	542 083

A more detailed approach resulted in a more accurate estimate of the number of users of the entire system of public transport. As a result, the process of calibration of the Warsaw simulation model was much easier.

VII. CONCLUSIONS

Even a highly automated urban transport system such as a metro is characterised by a certain variability of travel time. What can be observed is a decrease in transportation speeds during peak hours and speed increase in the evenings. Average running times and random components of running times on the sections between stations can be very precisely estimated on the basis of their length, regardless of the period of the day. The frequency runs up to as high as 20 trains per hour does not significantly influence the average running time. However, stations stops definitely have a greater influence on the variability of travel time. Average values for dwell times and their random components were determined for 3 basic station types, dependent on the location of the station relative to the inner centre.

The presented model for the travel time of the metro line, can be used as an input to the macro-simulation models of cities with metro systems. The results of parameter estimation of the model are of local character and depict current and future operational conditions of the first metro line in Warsaw. However, they can be adjusted to local conditions in other cities.

Further work on the halt times will aim at including the size of passenger flows.

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