18th International Conference on the Application of Computer
Science and Mathematics in Architecture and Civil Engineering
K. Gürlebeck and C. Könke (eds.)
Weimar, Germany, 07–09 July 2009

RELIABILITY OF TRAM-NETWORK SECTION

M. Bauer *, M. Dudek and M. Richter

** Cracow University of Technology, Chair of Transport Systems, Ul. Warszawska 24, 31-155 Cracow, Poland*
E-mail: mbauer@transys.wil.pk.edu.pl

Keywords: Traffic Engineering, Reliability, Public Transport Systems

Abstract. *The paper investigates aspects of tram-network section reliability, which operates as a part of the model of whole city tram-network reliability. Here, one of the main points of interest is the chronological development of the disturbances on subsequent sections, which are defined as difference between time of departure provided in schedule and real time of departure. These developments were observed in comprehensive measurements done in Krakow, during one of the main transportation nodes (Rondo Mogilskie) rebuilding. All taken building activities cause big disturbances in tram lines operation with effects extended to neighboring sections. In a second part, the stochastic character of section running time will be analyzed more detailed. There will be taken into consideration sections with only one beginning stop and also with two or three beginning stops located at different streets at an intersection. Possibility of adding results from sections with two beginning stops to one set will be checked with suitable statistical tests which are used to compare the means of the two samples. Section running time may depend on the value of gap between two following trams and from the value of deviation from schedule. This dependence will be described by a multi regression formula. The main measurements were done in the city center of Krakow in two stages: before and after big changes in tramway infrastructure.*

1 INTRODUCTION

In the context of this article, reliability of tram-network is defined as the probability, that the travel time on the selected route does not exceed a predetermined value. One of the most important features of public transport operation is punctuality. It is essential to passenger and operator. For the operator it is a measure to declare the level of service, specified in contract with ordering entity. It has also an effect on public transport demand increasing. For passenger, high punctuality is a base for detailed trip planning (particularly in cases of low frequency of public transport operation). One of the main questions is the character of mutual dependence or independence of the disturbances, which are defined as difference between time of departure provided in schedule and real time of departure. This question will be investigated in Section 2 using the results of comprehensive measurements done in Krakow, during one of the main transportation nodes (Rondo Mogilskie) rebuilding.

In a second part, the stochastic character of section running time will be analyzed more detailed. Running time at a section is defined as time between the moments of departure from the beginning stop until stopping at the end of this section. In former investigations (e.g. [3,5]) only a dependence on the parameters of the tram section (as length, number of intersections and kind of separation from the motorized individual traffic) was considered. The traffic volume was not taken into account. To improve the model, in Section 3 the influence of the value of gap between two following trams (as measure of this traffic volume) and the value of deviation from schedule on the running time will be investigated. This dependence will be described by a multi regression formula.

There will be taken into consideration sections with only one beginning stop and also with two or three beginning stops located at two different streets at an intersection. Possibility of adding results from sections with several beginning stops to one set will be checked with suitable statistical tests which are used to compare the means of the samples.

The main measurements were done in the city center of Krakow in two stages: before and after big changes in tramway infrastructure, with taking into consideration variability of tram traffic volume and different periods of average working day. At the end of the analysis, the model of tram-network section reliability will be supplemented. It will reflect variability of tram traffic volume and real time intervals between trams. This model should operate as a significant part of reliability model for the whole tram-network.

2 DISRUPTIONS ON THE TRAM-NETWORK SECTIONS IN KRAKOW

As a basic measure of punctuality is defined the deviation from schedule, which states the difference between time of departure t_r provided in schedule and real time of departure t_e,

$$d = t_r - t_e .$$

A positive value of this deviation refers to earliness of departure, and a negative value to lateness of departure, respectively. In various cities, values of tolerance for punctual departure are different, but always delays are less troublesome for passenger than too early departure. In some of cities, every earlier departure is evaluated as unpunctual, very often only two minutes of lateness is permissible. For example, in Krakow, punctually departure is from maximum one minute early and maximum three minutes late. The knowledge of deviations from schedule is necessary for calculation of punctuality indicators.

One of the biggest problems in public transport operation is keeping punctuality on the whole distance from first to last stop on the line. Especially in city centre area, vehicles operate in various and variable conditions, running times of following trams can differ significantly even in short periods. If schedule is well constructed, probability of earlier departures is very small, delays happen more often. But sometimes delays are too big, and tram which is really strongly delayed, for passengers waiting on stop, seems as early. Big delays are also disadvantageous because of line coordination with other tram or bus lines. That’s why the drivers should try to keep high punctuality as long as possible.

There are two most important questions: Is it possible to decrease delays at the following sections of the line? How often areas with sources of disturbances preceded departures before scheduled time? To get answers to these questions an analysis of departures punctuality on significant parts of two tram lines (No. 4 and No. 5) which operate in city centre area in Krakow was done. Both lines have diametric character and pass the city center (Figure 2.1). Moreover, the considered lines are very important for whole tram network in Krakow.

Measurements were being realized in vehicles moving along the line, during peak hours, in 2005, when Lubicz street was being rebuilt. Overall, 14 courses in both directions were measured on each line. In that time, tramways used elongated route. On the distance Dworzec Główny – Rondo Mogilskie, instead of steady, shortest route (only 3 stops), they had to use longer path (6 stops). Sections situated between stops: Basztowa LOT and Rondo Mogilskie are particularly susceptible for disruptions, especially during Lubicz street rebuilding, when large number of lines is concentrated.

To detailed analysis of punctuality there were taken into consideration sections with possible sources of disruptions, and also sections located before and after those sections. This kind of approach makes possibility of exact dividing the sections with big and low values of deviation from schedule. Registered moments of departures from following stops have been compared with times from schedules (in minutes).

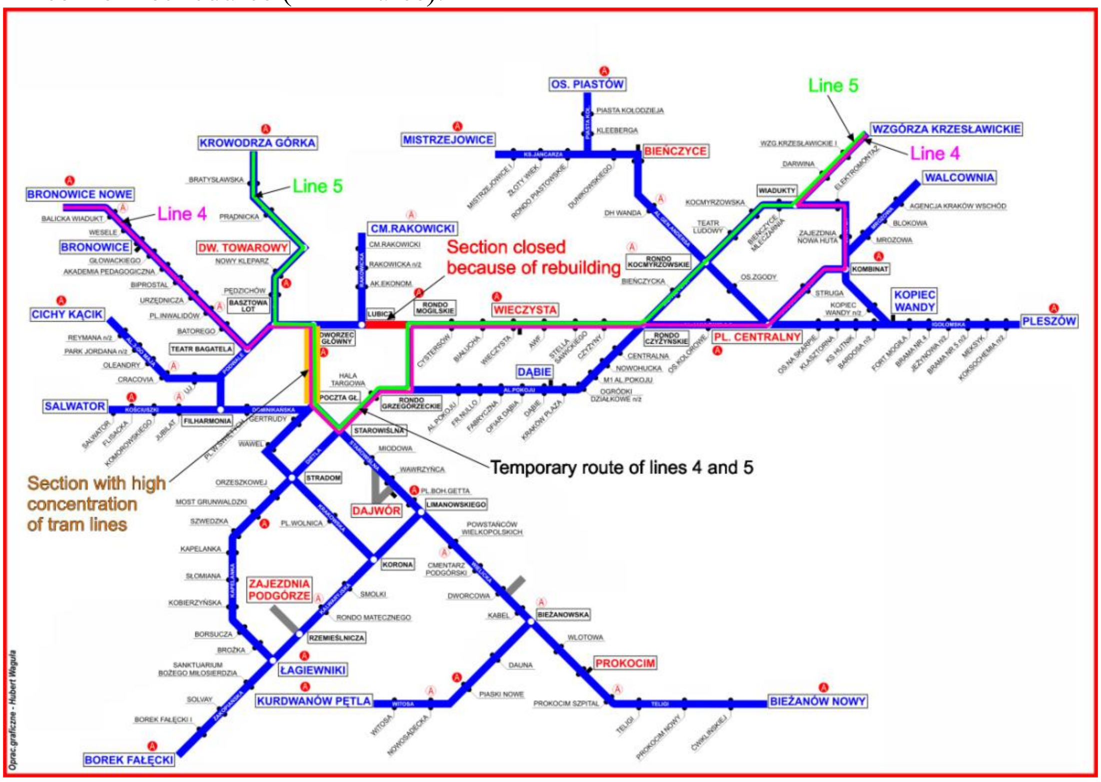

Figure 2.1. Tram-network in Krakow (*www.mpk.krakow.pl* [7]) with a trace of lines 4 and 5.

Deviations on line no. 5 are presented on Figure 2.2 and 2.3, and the results for line no. 4 are shown on Figures 2.4 and 2.5, respectively. On those pictures, additionally the average values of deviations are shown, with taking into consideration the ranges defined by mean value +/- standard deviation.

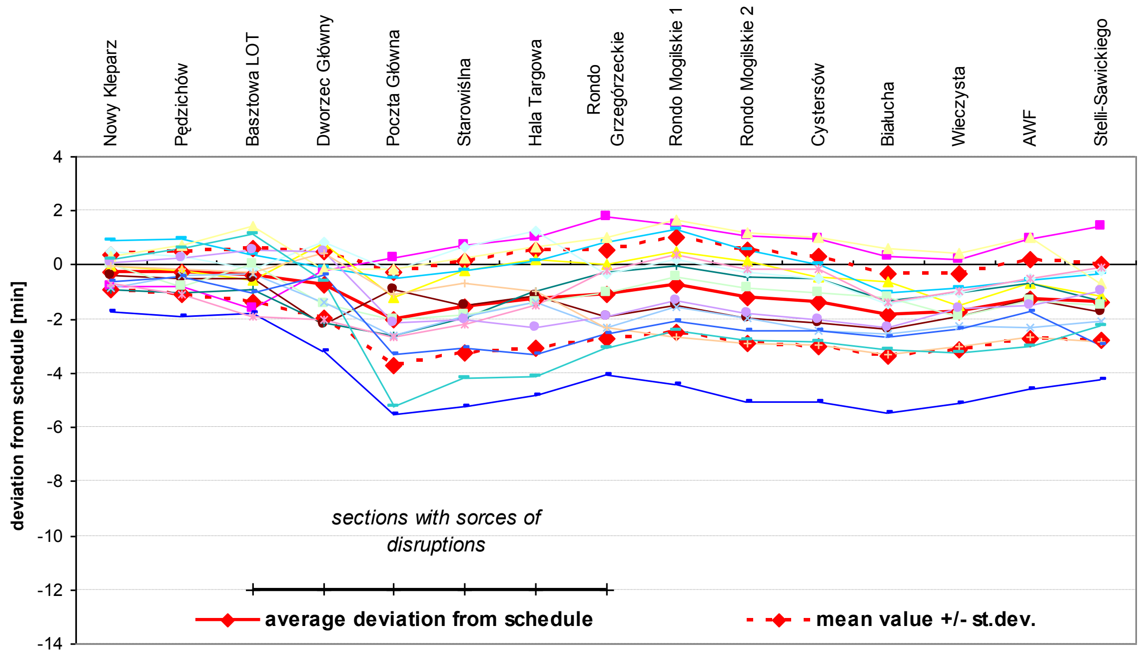

Figure 2.2. Deviations from schedule – line No. 5 during afternoon peak hour (direction: Krowodrza Górka – Wzgórza Krzesławickie).

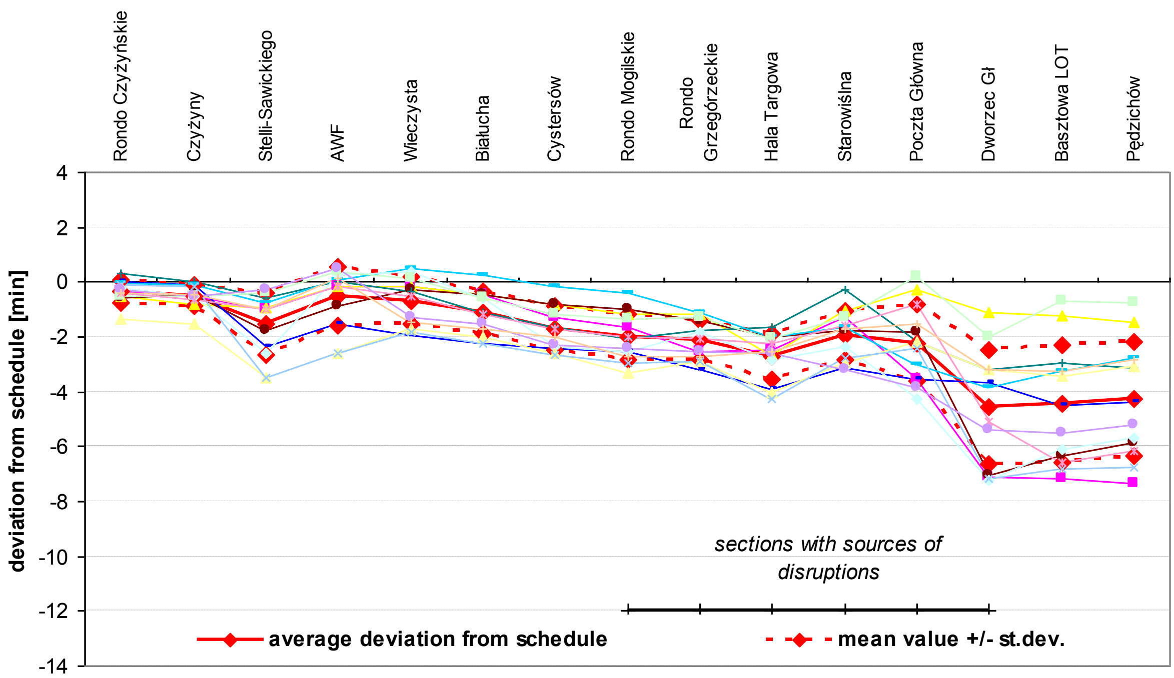

Figure 2.3. Deviations from schedule – line No. 5 during afternoon peak hour (direction: Wzgórza Krzesławickie – Krowodrza Górka).

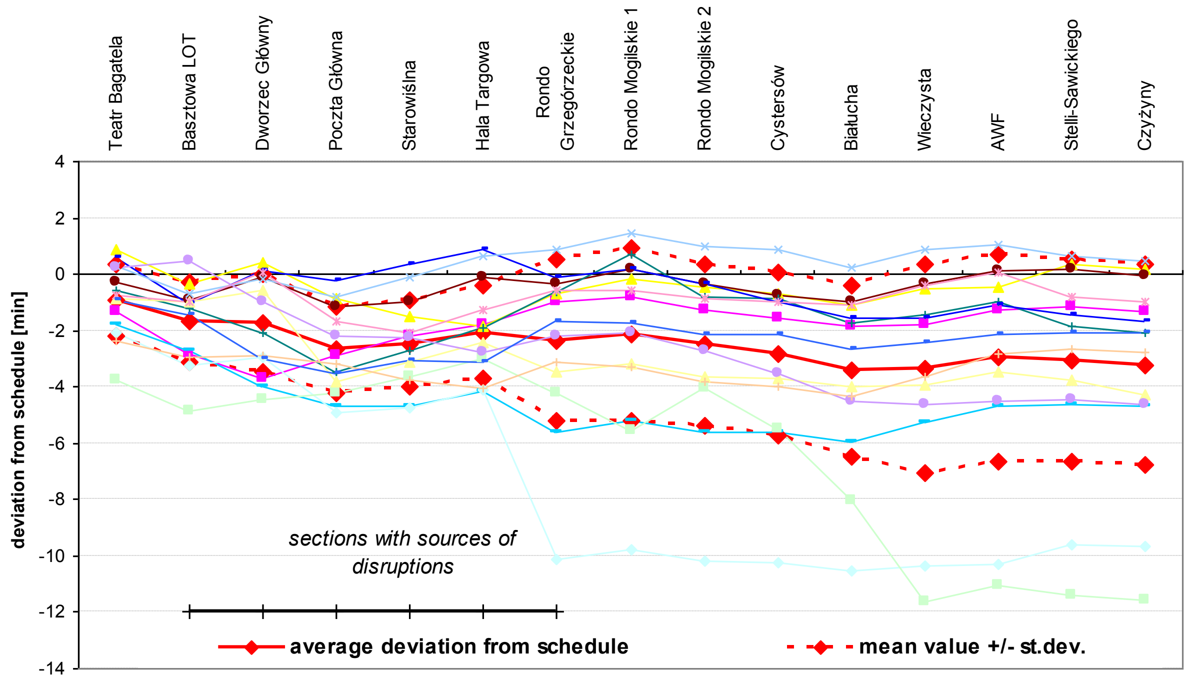

Figure 2.4. Deviations from schedule – line No. 4 during afternoon peak hour (direction: Bronowice Nowe – Wzgórza Krzesławickie).

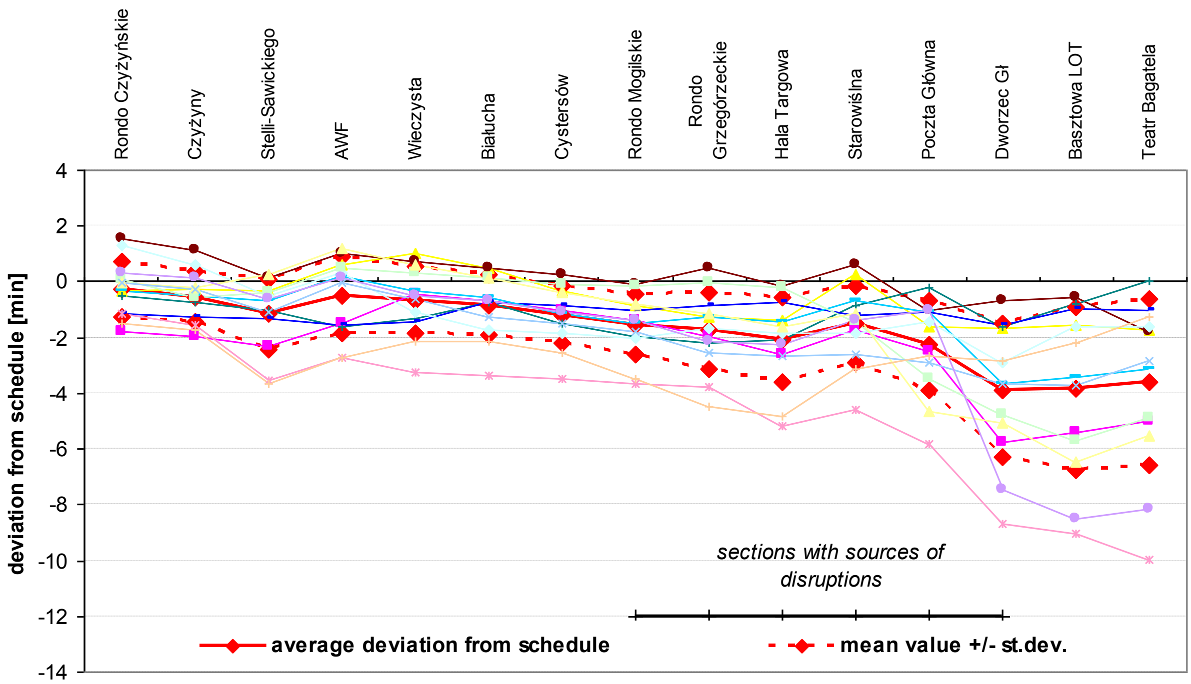

Figure 2.5. Deviations from schedule – line No. 4 during afternoon peak hour (direction: Wzgórza Krzesławickie – Bronowice Nowe).

On both lines and both directions, disruptions of punctuality begin on the previously mentioned sections with possible sources of those disruptions. On line no. 5, in first direction, average punctuality is very good (maximum 2 minutes delays), but in single cases earlier departures and five minutes delays happened. This variability begins on section Dworzec Główny – Poczta Główna and later stays on the same level. In case of second direction, there was observed considerable increase of delays on the same section.

Exampled normality plots for deviations on line no. 5 are shown on Figure 2.6. Here, data are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line. Deviations from this line indicate deviations from normality. The assumption of normal distribution states much stronger after Chi-square and Kolmogorov tests applying. In this way, distributions of deviations on stops were nearly in all cases fitted to Normal distribution. Similar results take place in case of opposite direction and line no. 4.

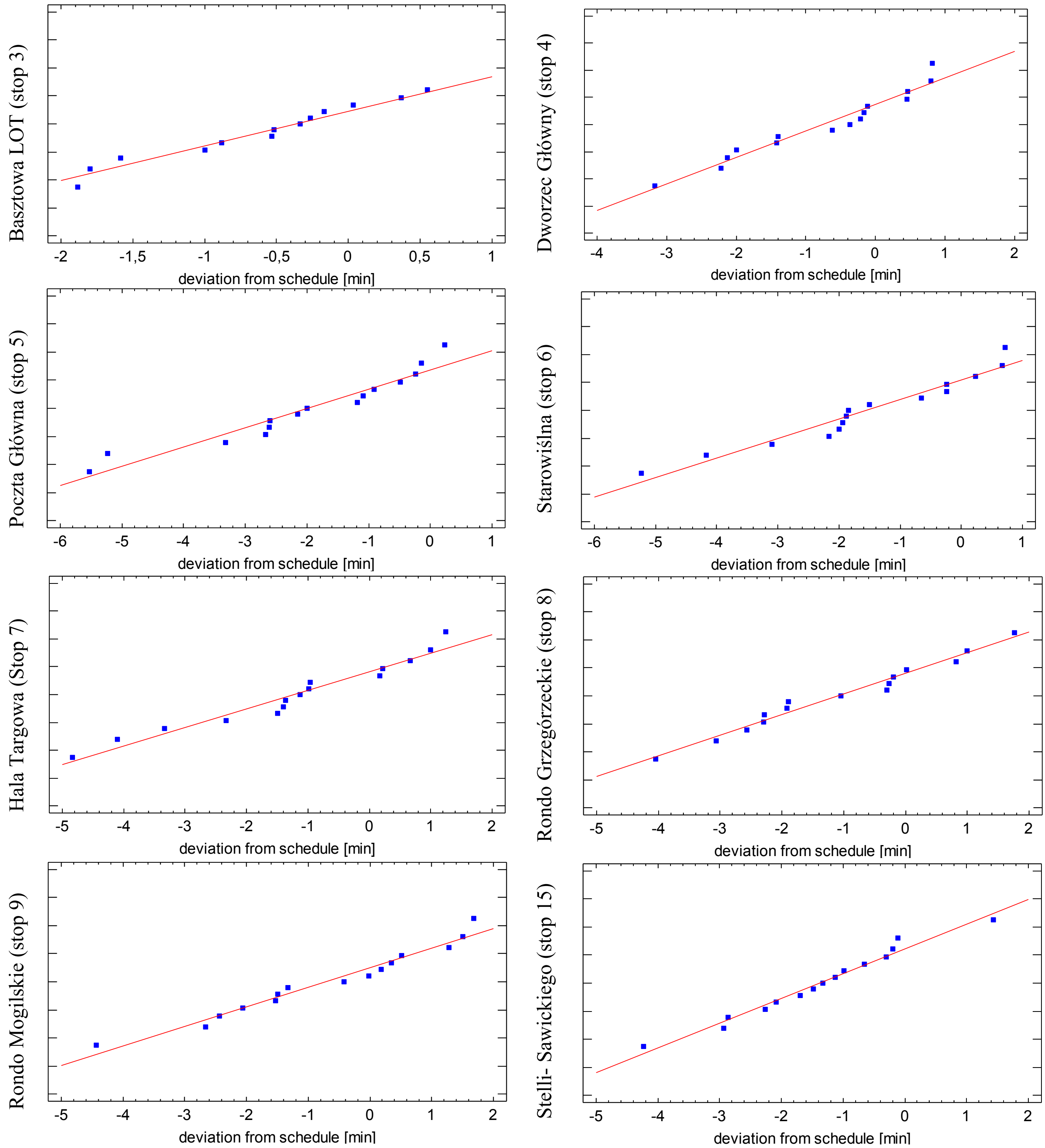

Figure 2.6. Normality plots for deviations from schedule for departures from stops – line 5 *(direction: Krowodrza Górka – Wzgórza Krzesławickie)*.

In further analysis the means and the standard deviations of the two samples were analysed more detailed. The results are presented in Table 2.1.

Stop		Feature	Deviation from schedule [min]	
			Average	St. deviation
Direction 1	Basztowa LOT	beginning of main part of line	**-0,36**	**0,99**
	Dworzec Główny	main part of line	**-0,75**	**1,23**
	Poczta Główna	main part of line	**-2,00**	**1,74**
	Hala Targowa	main part of line	**-1,56**	**1,72**
	Rondo Grzegórzeckie	main part of line	**-1,24**	**1,81**
	Rondo Mogilskie 1	end of main part of line	**-1,09**	**1,66**
	Stelli Sawickiego	distant stop	**-1,39**	**1,39**
Direction 2	Rondo Czyżyńskie	distant stop	**-0,34**	**0,39**
	Rondo Mogilskie	beginning of main part of line	**-2,11**	**0,73**
	Rondo Grzegórzeckie	main part of line	**-2,71**	**0,83**
	Hala Targowa	main part of line	**-1,93**	**0,90**
	Poczta Główna	main part of line	**-2,23**	**1,39**
	Dworzec Główny	main part of line	**-4,55**	**2,09**
	Basztowa LOT	end of main part of line	**-4,44**	**2,15**

Table 2.1: Results of two means test for deviations from schedule – line no. 5.

Stop		Feature	Deviation from schedule [min]	
			Average	St. deviation
Direction 1	Basztowa LOT	beginning of main part of line	**-1,70**	**1,42**
	Dworzec Główny	main part of line	**-1,73**	**1,73**
	Poczta Główna	main part of line	**-2,68**	**1,53**
	Hala Targowa	main part of line	**-2,46**	**1,55**
	Rondo Grzegórzeckie	main part of line	**-2,07**	**1,65**
	Rondo Mogilskie 1	end of main part of line	**-2,35**	**2,87**
	Stelli Sawickiego	distant stop	**-3,04**	**3,58**
Direction 2	Rondo Czyżyńskie	distant stop	**-0,27**	**0,99**
	Rondo Mogilskie	beginning of main part of line	**-1,54**	**1,09**
	Rondo Grzegórzeckie	main part of line	**-1,75**	**1,36**
	Hala Targowa	main part of line	**-2,07**	**1,52**
	Poczta Główna	main part of line	**-1,51**	**1,37**
	Dworzec Główny	main part of line	**-2,27**	**1,62**
	Basztowa LOT	end of main part of line	**-3,87**	**2,40**

Table 2.1: Results of two means test for deviations from schedule – line no. 4.

The biggest values of delay we can see in case of ends of considered sections. Those results show that drivers cannot decrease delays on farther sections of lines. If schedule is well constructed and traffic conditions are not so tough, trams should keep little (1 minute) delays, without a risk of earlier departures. If not, there is big probability of delay's increasing, especially in city center areas. There were also some courses, on which drivers tried to arrive to the city center with little earliness, and then keep little delays on the most difficult sections. Those activities should be forbidden.

Another observation is connected with standard deviation of deviation from schedule. It increases along the line, and if is too big at the first part of line, punctuality on farther stops will be very random.

It should be mentioned, that because of the normal distribution several tests for checking the hypothesis, that differences of delays on subsequent sections are statistically significant are possible, for instance t-tests for paired samples. For the sake of shortness, for the results of such tests reference is made to the talk. Additionally, the results are available from the authors upon request. In Section 3 another approach to describe the dependence of disturbances at subsequent sections is chosen.

3 VELOCITY AND RUNNING TIME OF SELECTED TRAM-NETWORK SECTIONS IN DEPENDENCE ON TRAFFIC VOLUME AND DEVIATION FROM TIME TABLE

As mentioned above, in the context of this article, reliability of tram-network is defined as the probability, that the travel time on the selected route does not exceed a predetermined value which is average value used in schedule designing [1,4,6]. For other definitions of reliability reference is made for instance to [2]. Clearly, the number of trams operating on the route has a significant influence on the travel time. On the one hand, the hourly number of trams on each section depends on part of the day. On the other hand, also disturbances in the normal traffic behaviour of the network have a large impact on the traffic volume. This impact is as larger as the traffic volume under normal circumstances is. Particularly, in the city center, where many tram lines are concentrated this effect can be observed in an exceptionally evident way. The considerations of this section concentrate on an analysis of the city center of Krakow from the traffic engineering point of view. Comprehensive measurements were done in the city center in two stages. The first measurements were done in 2006, the following in 2008. In the meantime big changes in tramway infrastructure occurred. Especially the tram route following Pawia Street was built and several other tram routes around the observation area which have influence on the corresponding traffic volume were changed. The stops, where the measurements were done are shown in Figure 3.1.

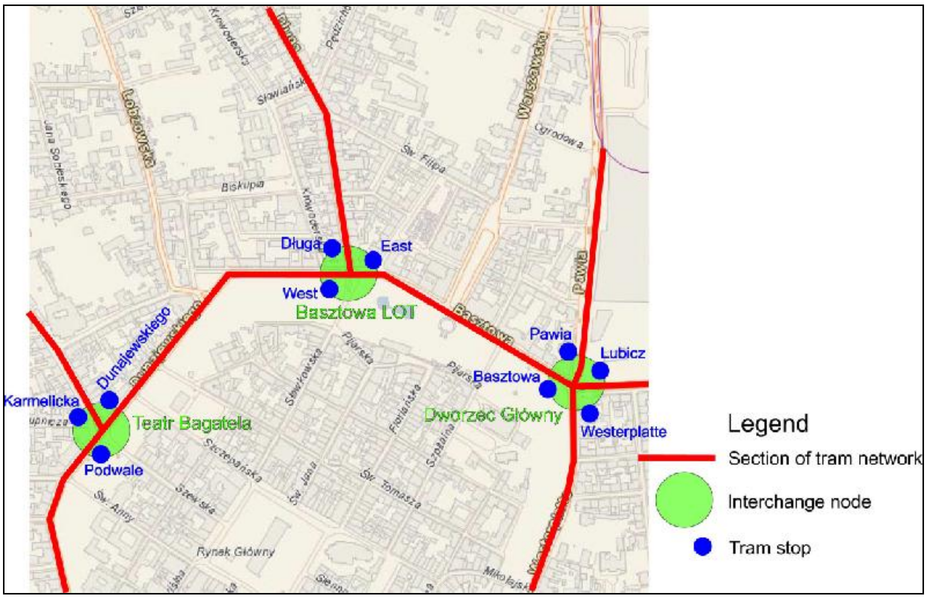

Figure 3.1 Tram network in city center of Krakow, measurement stops

The running time (which is defined as time between the moment of departure from the beginning stop of the section and the moment of stopping at the end of this section) is a main indicator for the reliability. Here, in the main focus of interest is the *travel speed,* which enables in an easy way the comparison of sections which different length. As independent variables which have influence on the travel time or the speed were considered

- n, the number of trams on the link before the analyzed section and
- s_e , the delay on the end stop of the link.

Both values seem to characterize the disturbances in tram line operation in neighbouring sections in a suitable way. Instead of s_e also the consideration of

- $s_{a,}$, the delay on the beginning stop of the link

would be possible. ,A comprehensive regression analysis was done to check the influence of these variables to travel time and velocity, respectively. Especially well-known regression methods were applied. In the first case, with an ordinary least square method, a relation in the form

$$Y_i = a_0 + a_1 X_{i1} + a_2 X_{i2} + \varepsilon_i$$

is assumed, where Y_i stands for the realizations of the dependent variable and X_{i1} and X_{i2} stand for the corresponding realizations of the independent variables, respectively. The variables ε_i are random disturbance terms fulfilling the usual assumption of independence. Because in some situations a quadratic influence of one independent variable (namely the number of trams on the link before the analyzed section) seems to be more promising, a more general ansatz of the form

$$Y_i = a_0 + a_1 X_{i1}^2 + a_2 X_{i2} + \varepsilon_i$$

is checked, however the mathematical background is because of the simple transformation to the squared data nearly the same. Clearly, other quadratic functions would be possible, which were checked but did not lead to better results.

In consequence, the following situations were checked more detailed:

- Linear function, $X_{i1}=n_i$ (number of trams on the link before analyzed section) as only influence,
- Quadratic function, $X_{i1}= n_i$ (number of trams on the link before analyzed section) as only influence,
- Linear function, $X_{i1}= n_i$ (number of trams on the link before analyzed section) and $X_{i2}=s_{ai}$ (delay on the beginning stop of the link),
- Linear function, $X_{i1}= n_i$ (number of trams on the link before analyzed section) and $X_{i2}=s_{ei}$ (delay on the end stop of the link),
- Quadratic function, $X_{i1}= n_i$ (number of trams on the link before analyzed section) and $X_{i2}=s_{ai}$ (delay on the beginning stop of the link),
- Quadratic function, $X_{i1}= n_i$ (number of trams on the link before analyzed section) and $X_{i2}=s_{ei}$ (delay on the end stop of the link),

Note, that in any case the dependent variable is either the running time (T) or the velocity (V). The best results were obtained for the second and sixth situation. The preference of the variable s_e instead of s_a can be explained by the fact, that the experienced tram drivers very often anticipate the situation on the last part of section and could influence onto running time by faster or slower driving. Table 3.1 shows the results of the regression analyses. There, the number of section consists of three parts. The first digit stands for the year of measurements (6 for 2006 and 8 for 2008, respectively). The second digit (1-4) describes the number of the considered section, with the meaning

1 Dworzec Główny (Main Railway station) – Basztowa LOT
2 Basztowa LOT – Teatr Bagatela
3 Teatr Bagatela – Basztowa LOT
4 Basztowa LOT – Dworzec Główny (Main Railway station)

The third digit in the number of section corresponds to the specific feature, that one tram stop (note that the chosen stops are situated close to intersections) in general consists of several stopping points, arranged on different access roads of the corresponding intersection. For more details, see Figure 3.1.

611 section Dworzec Główny (Main Railway station) (Lubicz Street) – Basztowa LOT	
$T = 0{,}2413 \cdot n^2 + 1{,}503$	$r^2 = 63{,}4\%$
$T = 0{,}2337 \cdot n^2 + 0{,}04017 \cdot s_e + 1{,}436$	$r^2 = 64{,}4\%$
$V = -1{,}118 \cdot n^2 + 17{,}34$	$r^2 = 62{,}3\%$
$V = -1{,}086 \cdot n^2 - 0{,}1719 \cdot s_e + 17{,}63$	$r^2 = 63{,}1\%$

612 section Dworzec Główny (Main Railway station) (Westerplatte Street) – Basztowa LOT	
$T = 0{,}2495 \cdot n^2 + 1{,}443$	$r^2 = 65{,}4\%$
$T = 0{,}2482 \cdot n^2 + 0{,}00455 \cdot s_e + 1{,}440$	$r^2 = 65{,}4\%$
$V = -1{,}115 \cdot n^2 + 16{,}96$	$r^2 = 62{,}4\%$
$V = -1{,}105 \cdot n^2 - 0{,}03510 \cdot s_e + 16{,}98$	$r^2 = 62{,}5\%$

621 section Basztowa LOT (East) – Teatr Bagatela	
$T = 0{,}2408 \cdot n^2 + 1{,}543$	$r^2 = 35{,}8\%$
$T = 0{,}2411 \cdot n^2 - 0{,}001623 \cdot s_e + 1{,}547$	$r^2 = 35{,}8\%$
$V = -2{,}062 \cdot n^2 + 23{,}68$	$r^2 = 28{,}1\%$
$V = -2{,}067 \cdot n^2 + 0{,}03111 \cdot s_e + 23{,}62$	$r^2 = 28{,}1\%$

622 section Basztowa LOT (Dluga Street) – Teatr Bagatela	
$T = 0{,}2309 \cdot n^2 + 1{,}682$	$r^2 = 32{,}9\%$
$T = 0{,}2047 \cdot n^2 + 0{,}09261 \cdot s_e + 1{,}548$	$r^2 = 44{,}9\%$
$V = -1{,}798 \cdot n^2 + 20{,}98$	$r^2 = 31{,}2\%$
$V = -1{,}587 \cdot n^2 - 0{,}7446 \cdot s_e + 22{,}05$	$r^2 = 43{,}3\%$

631 section Teatr Bagatela (Podwale Street) – Basztowa LOT	
$T = 0{,}1968 \cdot n^2 + 1{,}659$	$r^2 = 47{,}2\%$
$T = 0{,}1959 \cdot n^2 -0{,}000179 \cdot s_e + 1{,}664$	$r^2 = 47{,}4\%$
$V = -1{,}451 \cdot n^2 + 22{,}05$	$r^2 = 38{,}5\%$
$V = -1{,}437 \cdot n^2 + 0{,}002557 \cdot s_e + 21{,}98$	$r^2 = 38{,}9\%$

632 section Teatr Bagatela (Karmelicka Street) – Basztowa LOT	
$T = 0{,}1314 \cdot n^2 + 1{,}825$	$r^2 = 33{,}1\%$
$T = 0{,}1163 \cdot n^2 +0{,}1049 \cdot s_e + 1{,}692$	$r^2 = 41{,}5\%$
$V = -0{,}8732 \cdot n^2 + 19{,}32$	$r^2 = 25{,}7\%$
$V = -0{,}8587 \cdot n^2 - 0{,}03842 \cdot s_e + 19{,}34$	$r^2 = 25{,}7\%$

641 section Basztowa LOT (West) – Dworzec Główny (Main Railway station)	
$T = 0{,}1635 \cdot n^2 + 1{,}849$	$r^2 = 35{,}7\%$
$T = 0{,}1637 \cdot n^2 - 0{,}000153 \cdot s_e + 1{,}850$	$r^2 = 35{,}7\%$
$V = -0{,}7647 \cdot n^2 + 15{,}83$	$r^2 = 34{,}1\%$
$V = -0{,}7644 \cdot n^2 - 0{,}000418 \cdot s_e + 15{,}84$	$r^2 = 34{,}1\%$

642 section Basztowa LOT (Dluga Street) – Dworzec Główny (Main Railway station)	
$T = 0{,}1755 \cdot n^2 + 1{,}772$	$r^2 = 40{,}1\%$
$T = 0{,}1542 \cdot n^2 + 0{,}1662 \cdot s_e + 1{,}642$	$r^2 = 50{,}6\%$
$V = -0{,}7855 \cdot n^2 + 15{,}42$	$r^2 = 39{,}8\%$
$V = -0{,}6964 \cdot n^2 - 0{,}6969 \cdot s_e + 15{,}96$	$r^2 = 49{,}0\%$

811 section Dworzec Główny (Main Railway station) (Lubicz Street) – Basztowa LOT	
$T = 0{,}2385 \cdot n^2 + 1{,}572$	$r^2 = 54{,}4\%$
$T = 0{,}2316 \cdot n^2 + 0{,}02347 \cdot s_e + 1{,}523$	$r^2 = 55{,}5\%$
$V = -1{,}283 \cdot n^2 + 17{,}64$	$r^2 = 45{,}1\%$
$V = -1{,}250 \cdot n^2 - 0{,}1128 \cdot s_e + 17{,}88$	$r^2 = 45{,}9\%$
812 section Dworzec Główny (Main Railway station) (Westerplatte Street) – Basztowa LOT	
$T = 0{,}1978 \cdot n^2 + 1{,}940$	$r^2 = 46{,}1\%$
$T = 0{,}1842 \cdot n^2 + 0{,}03571 \cdot s_e + 1{,}874$	$r^2 = 49{,}6\%$
$V = -0{,}8529 \cdot n^2 + 14{,}03$	$r^2 = 34{,}8\%$
$V = -0{,}7906 \cdot n^2 - 0{,}1637 \cdot s_e + 14{,}33$	$r^2 = 37{,}7\%$
813 section Dworzec Główny (Main Railway station) (Pawia Street) – Basztowa LOT *(this route has been operating since 2008)*	
$T = 0{,}2852 \cdot n^2 + 1{,}761$	$r^2 = 70{,}8\%$
$T = 0{,}2638 \cdot n^2 + 0{,}08519 \cdot s_e + 1{,}683$	$r^2 = 73{,}0\%$
$V = -1{,}017 \cdot n^2 + 14{,}96$	$r^2 = 54{,}9\%$
$V = -0{,}9595 \cdot n^2 - 0{,}2293 \cdot s_e + 15{,}17$	$r^2 = 55{,}8\%$
821 section Basztowa LOT (East) – Teatr Bagatela	
$T = 0{,}1887 \cdot n^2 + 1{,}719$	$r^2 = 39{,}4\%$
$T = 0{,}1869 \cdot n^2 + 0{,}008763 \cdot s_e + 1{,}702$	$r^2 = 39{,}7\%$
$V = -1{,}471 \cdot n^2 + 21{,}42$	$r^2 = 34{,}0\%$
$V = -1{,}464 \cdot n^2 - 0{,}03646 \cdot s_e + 21{,}46$	$r^2 = 34{,}1\%$
822 section Basztowa LOT (Dluga Street) – Teatr Bagatela	
$T = 0{,}2821 \cdot n^2 + 1{,}641$	$r^2 = 60{,}6\%$
$T = 0{,}2600 \cdot n^2 + 0{,}02913 \cdot s_e + 1{,}654$	$r^2 = 61{,}8\%$
$V = -1{,}997 \cdot n^2 + 20{,}94$	$r^2 = 60{,}8\%$
$V = -1{,}886 \cdot n^2 - 0{,}1469 \cdot s_e + 20{,}88$	$r^2 = 61{,}4\%$
831 section Teatr Bagatela (Podwale Street) – Basztowa LOT	
$T = 0{,}1903 \cdot n^2 + 1{,}697$	$r^2 = 45{,}6\%$
$T = 0{,}1825 \cdot n^2 + 0{,}05162 \cdot s_e + 1{,}597$	$r^2 = 49{,}4\%$
$V = -1{,}318 \cdot n^2 + 21{,}49$	$r^2 = 34{,}4\%$
$V = -1{,}260 \cdot n^2 - 0{,}3804 \cdot s_e + 22{,}23$	$r^2 = 37{,}7\%$
832 section Teatr Bagatela (Karmelicka Street) – Basztowa LOT	
$T = 0{,}1846 \cdot n^2 + 1{,}711$	$r^2 = 59{,}5\%$
$T = 0{,}1852 \cdot n^2 – 0{,}000610 \cdot s_e + 1{,}714$	$r^2 = 59{,}8\%$
$V = -1{,}090 \cdot n^2 + 20{,}00$	$r^2 = 53{,}8\%$
$V = -1{,}094 \cdot n^2 + 0{,}003161 \cdot s_e + 19{,}99$	$r^2 = 54{,}0\%$
841 section Basztowa LOT (West) – Dworzec Główny (Main Railway station)	
$T = 0{,}2831 \cdot n^2 + 1{,}219$	$r^2 = 41{,}8\%$
$T = 0{,}2831 \cdot n^2 - 0{,}000017 \cdot s_e + 1{,}219$	$r^2 = 41{,}8\%$
$V = -1{,}751 \cdot n^2 + 22{,}08$	$r^2 = 32{,}6\%$
$V = -1{,}751 \cdot n^2 - 0{,}000865 \cdot s_e + 22{,}09$	$r^2 = 32{,}6\%$
842 section Basztowa LOT (Dluga Street) – Dworzec Główny (Main Railway station)	
$T = 0{,}1517 \cdot n^2 + 1{,}476$	$r^2 = 18{,}6\%$
$T = 0{,}1283 \cdot n^2 + 0{,}08398 \cdot s_e + 1{,}480$	$r^2 = 26{,}8\%$
$V = -1{,}432 \cdot n^2 + 19{,}19$	$r^2 = 23{,}8\%$
$V = -1{,}255 \cdot n^2 - 0{,}6376 \cdot s_e + 19{,}16$	$r^2 = 30{,}6\%$

Table 3.1 Results of regression analyses

In Table 3.1 also the coefficient of determination r^2 is shown. It measures how well the regression line approximates the real data points. Unfortunately, in some cases this coefficient is far away from 100%, a fact that depreciates the regression results. Moreover, it can be seen, that the statistical influence of the variable s_e (delay on the end stop of the link) is very heterogeneous. Sometimes the regression coefficient is nearly zero (and corresponding tests show, that it can be neglected), sometimes the influence occurs with positive sign, sometimes with negative sign. Also the values of the coefficient a_0 and a_1 (which are often nearly the same, independent of the occurrence of s_e) confirm the result, that the correlation between V or T and s_e is not very strong. In contrast to this for instance in the model for the speed at the route Dworzec Główny (Lubicz Street) – Basztowa LOT the influence is significant (the regression coefficient in the quadratic regression equals -0.1719). A more detailed analysis in Figure 3.2 shows, that this behaviour (negative correlation of s_e to V) occurs for every value of n. Negative value of this coefficient reflects running time extension caused by disruptions onto this section.

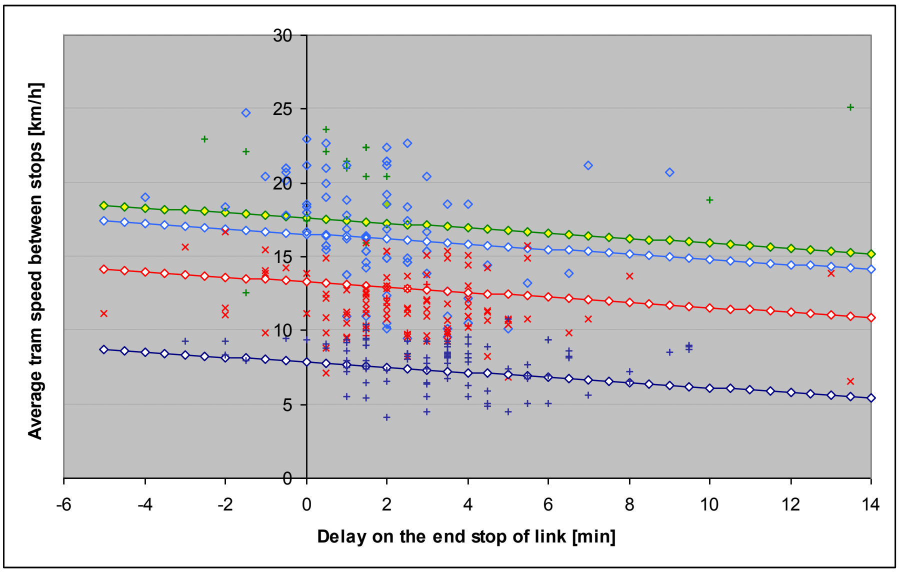

Figure 3.2 Relation between average tram speed between stops Dworzec Główny (Lubicz Street) – Basztowa LOT and delay on the end stop of link and number of trams on the link before analyzed tram (dark blue – n=0, red – n=1, light blue – n=2, green – n=3)

In contrast, at the route Basztowa LOT (West) – Teatr Bagatela there is no significant correlation (the regression coefficient in the quadratic regression equals -0.03646, see Figure 3.3 for a deeper analysis).

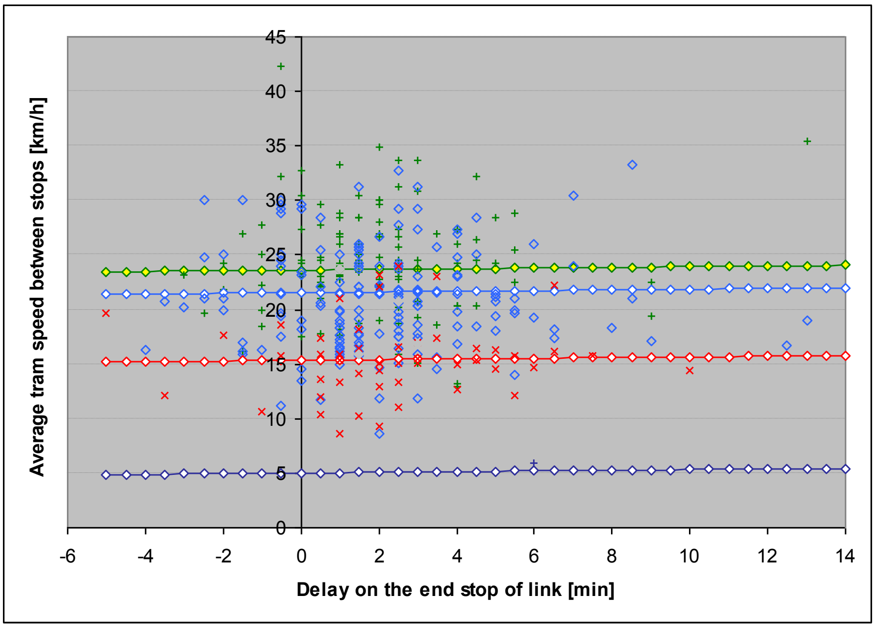

Figure 3.3 Relation between average tram speed between stops Basztowa LOT (West) – Teatr Bagatela and delay on the end stop of link and number of trams on the link before analyzed tram (dark blue – n=0, red – n=1, light blue – n=2, green – n=3)

In Figure 3.4, a comparison of the relation between n and the tram speed V for the considered routes is shown. It can be seen, that there are differences in the absolute values of the speed (depending on different traffic situations on corresponding routes). However, the general shape of the plotted functions is always the same, which speaks for the fact, that the quadratic influence of tram traffic volume (n) to velocity on the section (V) can be considered as a general result of the realized study. Moreover, from Figure 3.4 it can bee seen, that the third digit in the number of the route (i.e. the stopping point at the intersection) had in 2006 no influence on the considered relation in case of route Basztowa LOT – Teatr Bagatela (and vice versa). However, for the route Dworzec Glowny – Basztowa LOT (and vice versa) there are some differences. These may be caused by strong influence of traffic lights at the neighbouring intersections and from various traffic volumes of cars and pedestrians on intersection area.

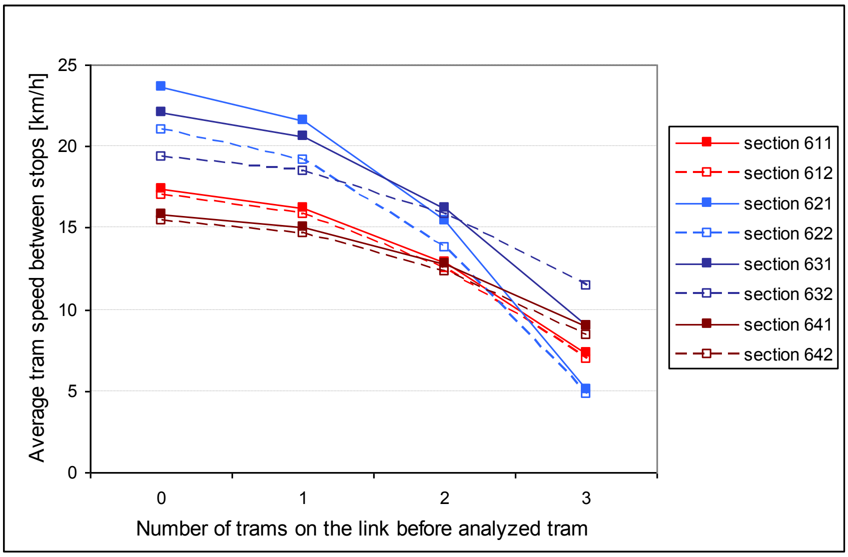

Figure 3.4 Influence of n (i.e. traffic volume) on V (average tram speed), year 2006

In the year 2008, in general larger differences with respect to different stopping points at the intersection occur, see Figure 3.4.

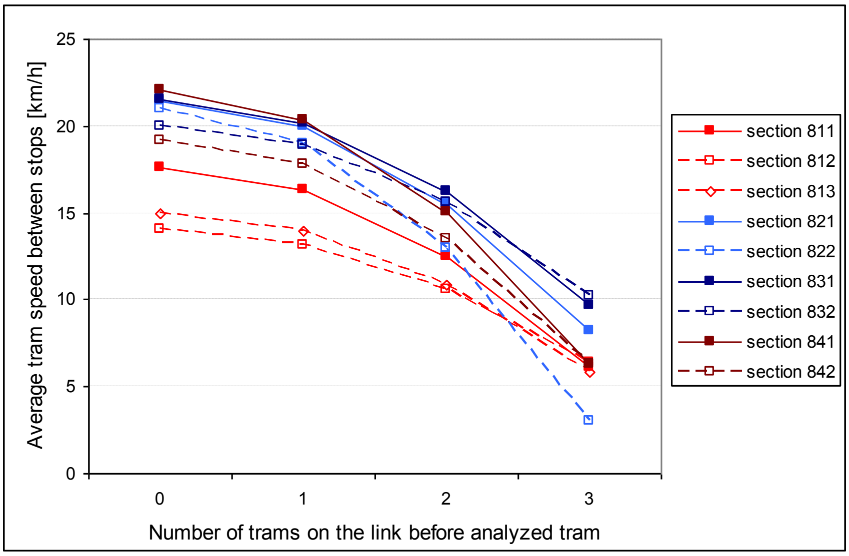

Figure 3.5 Influence of *n* (i.e. traffic volume) on *V* (average tram speed), year 2008

In a next step, the opportunity to summarize different stopping points around one intersection (described by the third digit in the number of the section) with the purpose of statistical analyses is checked more detailed. Table 3.2 shows the results of corresponding Mann-Whitney tests (in case of two stopping points) or Kruskal-Wallis tests (in case of three stopping points). Note, that these tests work without assumptions on the kind of distribution of the underlying random variables, i.e. normal distribution is not assumed. To be precise, the hypothesis that the distribution of *V* does not depend on the third digit in the number of the section is tested. In Table 3.2 the significance level of the corresponding tests is shown. Small values mean that there are significant differences and therefore an aggregation is not possible. In case of large values, the test does not contradict the aggregation of the data for statistical analysis. These values (in the present case values larger than 0.05) are emphasized. Note, that the situation 813 occurs only in 2008, since the corresponding stopping point has been built new.

Number of Sections	Significance Level	Number of Sections	Significance Level
611 + 612	***0.458***	811+812	0.000
		811+813	0.006
		812+813	***0.346***
		811+812+813	0.000
621 + 622	0.010	821+822	0.049
631 + 632	0.032	***831+832***	***0.462***
641 + 642	***0.695***	841+842	0.000

Table 3.2 Results of tests for aggregation of data (emphasized values mean, that aggregation is possible)

The results on the left hand side of Table 3.2 confirm the description given for Figure 3.4 very well. In the same way the results of the right hand side of Table 3.2 could be conjectured from Figure 3.5. It is remarkable, that the behaviour between 2006 and 2008 changed rapidly, which may be caused by significant intersection rebuilding (Dworzec Główny, new tram track in Pawia street) and switching off the signalization. It results by traffic relations changing on neighbouring intersections.

In Table 3.3 the results of regression with aggregated data is shown for the cases in which the aggregation was possible (see Table 3.2). It can bee seen, that the influence of s_e can be neglected in all these cases.

61 (611+612) section Dworzec Główny (Main Railway station) – Basztowa LOT	
$V = -1{,}116 \cdot n^2 + 17{,}14$	$r^2 = 62{,}2\%$
$V = -1{,}099 \cdot n^2 - 0{,}07024 \cdot s_e + 17{,}22$	$r^2 = 62{,}4\%$
64 (641+642) section Basztowa LOT – Dworzec Główny (Main Railway station)	
$V = -0{,}7703 \cdot n^2 + 15{,}63$	$r^2 = 36{,}1\%$
$V = -0{,}7701 \cdot n^2 - 0{,}000431 \cdot s_e + 15{,}63$	$r^2 = 36{,}1\%$
83 (831+832) section Teatr Bagatela – Basztowa LOT	
$V = -1{,}161 \cdot n^2 + 20{,}52$	$r^2 = 42{,}4\%$
$V = -1{,}163 \cdot n^2 + 0{,}002349 \cdot s_e + 20{,}52$	$r^2 = 42{,}4\%$

Table 3.3 Results of regression analyses (aggregated data)

In majority of cases, there are significant differences between velocities for common sections, beginning on different stops, but ending on the same stop. It is not possible to model velocity as one value for those kind of sections together. The reason of this situation are: various traffic conditions on following legs and different rights of way on intersections. On the picture below (Figure 3.6), there were presented only three cases, where velocities for common sections don't differ significantly.

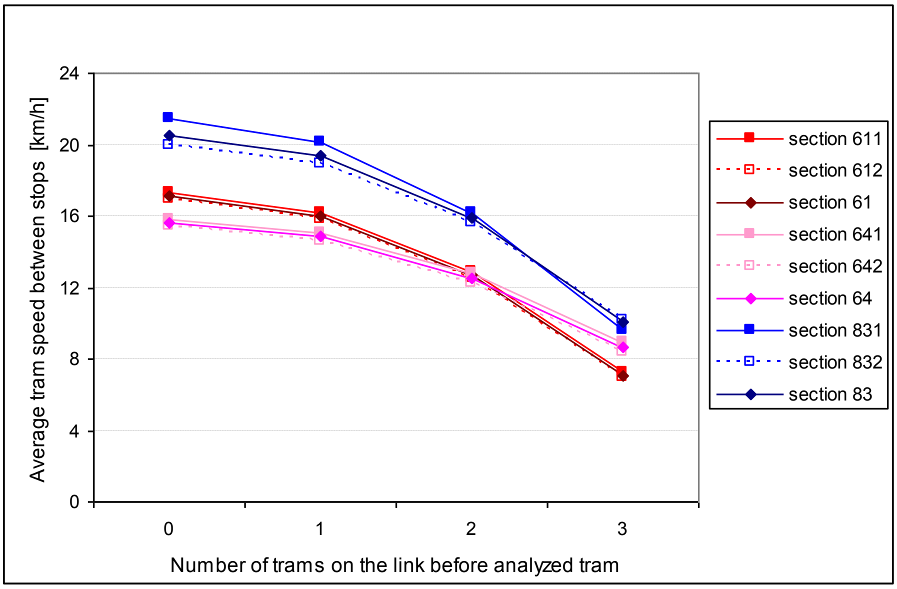

Figure 3.6 Comparison of 2006 and 2008 (Dworzec Główny (Main Railway station) – Basztowa LOT)

4 CONCLUSIONS

A detailed analysis of the influence factors to running time and velocity is of key importance for the investigation of reliability of the tram-network section. Beside parameters of the section (as length, number of intersections and kind of separation) also the traffic volume influences the running time and consequently the disturbances and deviations from time table. Moreover, disturbances on subsequent sections cannot be assumed to be stochastically independent. In the paper, on the basis of comprehensive measurements several statistical analyses were done. Here, the possibility to add results from sections with several beginning stops to one set was checked by suitable statistical methods. The results of regression analyses (especially the coefficients of determination) were not quite satisfying in all cases. The influence of current delay on the velocity could not be clarified conclusive. A unified model has still to be found and is in the viewpoint of further research.

REFERENCES

[1] M.O. Ball, C.J. Cobourn, J.S. Provan, Network reliability. M.O. Ball et al., eds. *Network Models. Handbooks in operations Research and Management Science*, vol. 7, Elsevier, Amsterdam, 1995.

[2] M.G.H. Bell, Y.Iida, *Transportation network analysys*, Wiley, Chichestser, 1997.

[3] Bauer M., Kandler A., Weiß, Model of tram line operation. *Internationales Kolloquium über Anwendungen der Informatik und Mathematik in Architektur und Bauwesen IKM2006*, Weimar, 2006.

[4] Dudek M., Richter M., Untersuchungen zur Zuverlässigkeit des Straßenbahnnetzes in Krakau. *Internationales Kolloquium über Anwendungen der Informatik und Mathematik in Architektur und Bauwesen IKM2006*, Weimar, 2006.

[5] Rudnicki A., *Jakość komunikacji miejskiej*. Kraków, 1999.

[6] A. Sumalee, D. Watling, Travel time reliability in a network with dependent link modes and partial driver response. *Journal of the Eastern Asia Society for Transportation Studies*, 5, 1686-1701, 2003.

[7] www.mpk.krakow.pl