TRANSPORT
ISSN 1648-4142 print / ISSN 1648-3480 online
2012 Volume 27(4): 428–433
doi:10.3846/16484142.2012.754378

CALCULATIONS OF TRAMWAY TRACK CAPACITY IN THE WIDE AREA NETWORKS

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Submitted 12 May 2011; accepted 28 June 2011

Abstract. The article shows a way of calculating the tram network capacity. A wide area network in Silesian Conurbation was used as an example (before and after planned modernization). Special attention was put on the traffic limiters like: single-track sections, stops, junctions, crossings with traffic lights, etc. Travel times and other characteristics were determined with the use of Monte Carlo method. In total, the capacity calculations of the tram network in Silesian Conurbation (divided into 74 sections) had taken into account: 131 crossings with traffic lights, 395 stops, 52 junctions, 51 single-track sections.

Keywords: tram, capacity, smoothness characteristics, modeling, simulation, smoothness limiter, tram stop, junction, single-track, traffic lights, travel time, occurrence time.

1. Introduction

Tram transport system is a very specific branch of transport in terms of mobility. It combines many characteristics of road and rail transport (Abril *et al.* 2008; Burdett, Kozan 2006; De Kort *et al.* 2003; Fernández 2010; Harrod 2009; Javadian *et al.* 2011; Fransoo, Bertrand 2000; Landex 2009). For this reason, calculating the capacity of tram track systems is a very complicated problem (Molecki 2008a; Nash *et al.* 2004). It is relatively simple to calculate the capacity in the case of newly built double-track routes, completely separated from the roadway. The problem is much more complicated in traditional networks, especially emerged at the turn of the 19th and 20th century. Such a problem was put on the team that worked up the 'Investment programme of tramway development for the years 2008–2013 for renovation and modernization of the tram network of the Upper Silesian Industrial District' in which authors of this paper took part.

2. Historical and Geopolitical Conditionings of Tram Network Techniques

The first line of a steam tram in Silesia, was built 1892, and opened in 1894. The first electric tram line was activated in 1898. The most dynamic development of the tram network lasted until the mid-30s of the 20th century. Initially, all routes were built as single-track with passing sidings. The first section was converted into a double-track in 1908. Nevertheless, still over 40% of the routes are single-track.

The specificity of the region caused significant technical network differentiation. At the time of formation of the first tram lines, the region was divided into German–Russian state border. Some parts of the routes were built as a typically urban, but most of them as local – connecting cities and villages. After Poland regained its independence in 1918, the network was still split into a German and Polish, whose borders have changed several times. These conditions resulted in considerable differentiation in routes at the beginning of their existence. Since the end of World War II, the whole network was in Poland.

In subsequent years there were undertaken a modernization as well as transformation of the network. New routes were built connecting large housing estates and industrial plants. Due to the development of bus routes, the countryside trams were closed down. In the years 1980–1982 the first route of rapid tram was completed (2.9 km in the deep trench without crossing the routes of other road users).

After the political transformation in 1989 a tram operating company remained national, which resulted in inhibition of modernization activities. In the years 1991–2000 only minor repairs of tracks and rolling stock were carried out. The exception was a modernization of a short section on the occasion of rebuilding a modernized road system in Katowice. In 2000, as a result of the reform of local government finance, the financing of trams broke down completely. The result was a growing level of degradation of the tracks and rolling stock. At the end of the first decade of the 21st century, the routes were being closed down not only for economic reasons, but also for their condition. To prevent the total elimination of the tram communication a wide modernization was planned.

Contemporary the tram network connects 13 cities out of the Upper Silesian Industrial Region (GOP). GOP is a group of several cities with a diverse population (from 33.4 thousand in Czeladz to 299.7 thousand in Katowice) and population density (from 678 person/km^2 in Dabrowa Gornicza to 3994 person/km^2 in Swietochlowice). In fact, the current urban boundaries are largely artificial and do not correspond to the actual urban structure. Some cities are polycentric, while at the same time there are consistent settlement units located in two different cities.

The diverse nature of the tram routes has been deepened by the lack of a common transport policy of these cities by a number of decades. In the eastern part of the network most of the routes are double track, almost all routes are separated from the roadway. In the central part the routes are mostly double track, but much of it goes in the streets. While in the western part the majority of tracks are single-track, but separated from the roadway. The lengths of the routes are within the limits from 1.6 km to 22.7 km. The basis of operation is still intercity traffic. Technical nature of many routes varies along their length. This causes additional maintenance problems.

3. Technical Parameters of the Network in Terms of the Planned Modernization

Within the tram network passenger traffic is handled by the 34 tram routes. In rush hour these routes are operated by 256 cars (202 trains). The tramway runs on four depots: in Bedzin, Bytom, Gliwice and Katowice. It is, in terms of length, one of the most extensive networks in concentrated urban areas in Europe (Fig. 1). Tram infrastructure is currently operated by the company Silesian Trams SA.

Since communalization in 2008 the local authorities and the company Silesian Trams Company have implemented renewal of rolling stock through modernization of tram-cars and major repairs of tracks. One of such projects is an attempt of radical improvement: safety, comfort, accessibility and capacity of tram traffic included in the 'Investment program of tramway development for the years 2008–2013 for renovation and modernization of the tram network of the Upper Silesian Industrial District' in which authors of this paper took part. Program, and the calculation of the associated capacity, was based on the development of investment variants, varying in scope of modernization of infrastructure. Determination of the effects of these activities, was related to the 'zero' variant (base case). As a part of this paper the characteristics of network capacity were set for the variant including modernization of the infrastructure (tracks, platform stops, and traction), the application of priorities on the modernized sections, the purchase of modern rolling stock and upgrading of existing, together with a partial shift of track – eliminating left turnings downtime. Modernization of track was extended in the following cities: Bytom, Chorzow, Katowice, Ruda Slaska, Sosnowiec, Swietochlowice and Zabrze.

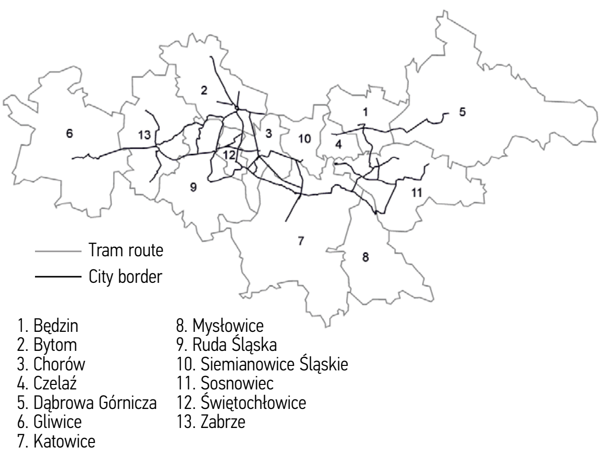

Fig. 1. Tramway network in Silesian Conurbation

4. The Theoretical Basis for the Calculation of Tram Network Capacity

4.1. Capacity Calculations of Single-Track Sections

The major limitation of the track capacity is of course two-way single-track sections. Traditionally, the capacity has been calculated according to the formula:

$$C = \frac{3600}{2 \cdot t_T + t_{Rv}}, \tag{1}$$

where: C – capacity [courses per hour in one direction]; t_T – section total travel time [s]; t_{Rv} – reserve time to maintain punctuality [s].

Such estimation is not precise (Molecki 2008a, 2008b). Difficulties arise mainly by the estimation of reserve time for the maintenance of punctuality. Time reserve is needed in the present conditions, because of interactions between trams and other road users. The frequency and nature of these interactions depend on many factors such as:

- length of tracks inseparable from the roadway;
- the number of crossroads, pedestrian crossings and railway crossings;
- traffic volume of other traffic participants;
- the way of traffic management.

In the paper, to make travel on single-track sections real, the Monte Carlo method was used. Multiple travel through a single track section was simulated, including crossroads, stops etc. The following formulas were used:

$$F(t_S) = \int_0^{t_S} \frac{1}{t \cdot \left(\frac{1}{2 \cdot N_P + 2} + 0.18 \right) \cdot \sqrt{2 \cdot \pi}} \times \exp\left(\frac{-(\ln(t) - \ln(32 - 27e^{-0.04 \cdot N_P}))^2}{2 \cdot \left(\frac{1}{2 \cdot N_P + 2} + 0.18 \right)^2} \right) dt, \tag{2}$$

where: $F(t_S)$ – distribution function of stop service time [–]; t – time [s]; t_S – stop service time [s]; N_P – number of passengers getting in or getting out at the stop [–];

$$F\left(t_{Rn}\right) = \int_0^{t_{Rn}} \frac{10}{t\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(\ln(t)-\ln(0.121\cdot s+5.5))^2}{0.02}}\,dt\,, \quad (3)$$

where: $F(t_{Rn})$ – distribution function of separated from track section travel time with no stoppages [–]; t – time [s]; t_{Rn} – section travel time with no stoppages [s]; s – distance [m].

In case the tracks were not separated from roads the travel time distribution was determined empirically, for each of the studied sections. Travel time for crossings without traffic lights has been determined similarly. Even if the tram has the right of way, many road vehicle drivers treat the surface of the crossing as a common area of accumulation. Therefore, all the crossings were under observation, on which basis the actual traffic conditions were determined.

In case of crossroads with traffic lights, a separate control procedure was designed, to allow or not allow the tram for passing in accordance with the actual traffic lights programme.

In case of accommodation traffic lights a constant programme with maximal length of cycle was used, because the capacity for rush hours was being studied. Due to the industrial character of the region in two places at railway crossings are operating only freight trains (Fig. 2).

Therefore, the frequency of closures was defined on the basis of the actual railway timetable. Time, according to the rail regulations applicable in Poland, having regard to the permissible speed of a train and a typical scheduled length of the train (defined indirectly through the mass of the train):

$$F\left(t_{RRC}\right) = \int_0^{t_{RRC}} \frac{0.1}{\sqrt{2\cdot\pi}}\cdot e^{\frac{-(t-150)^2}{200}}\,dt + \frac{m_{RT}}{80\cdot 10^3}\cdot\frac{14.1}{v_{RT}}\,, \quad (4)$$

where: $F(t_{RRC})$ – distribution function of railway crossing time closures [–]; t – time [s]; t_{RRC} – railway crossing time closures [s]; m_{RT} – mass of the railway train [kg]; v_{RT} – rail train speed within the railway crossing [m/s].

Both control procedures of railway crossings closure's and traffic lights operated independently of the trams appearance. This means that no hypothetical waiting time of the possibility of passing at the time of tram appearance was at random chosen, but it was only checked at the point of simulation procedure when a tram appears. The inputs conditions: such as moments of the start of traffic lights, as well as periods of closure of the railway crossings were at random drawn before the simulation of traffic on the route section. As a result, prior to the simulation, the windows allowing the passage were already known. On the basis of appearance of the tram to the object, waiting time for the opportunity to travel was determined. To avoid distortions caused by 'serendipity' and 'permanent bad luck', the simulation process was carried out repeatedly for different input conditions, and then the results were aggregated.

Fig. 2. Railway crossing on the tram route in Sosnowiec

An additional difficulty in determining the occupancy time of single-track sections was diverse control systems of occupancy check used in Silesian tram network. The following systems are in use:

- automatic occupancy control;
- requiring the manual signal adjustment after the tram driver's getting out;
- without control, operated on the basis of the timetable.

As a result of the simulation the expected travel time was set as:

$$E\left(t_T\right) = \sum_{i=1}^{n}\left(\sum_{p=1}^{p_{\max}} t_{S(i,p)} + \sum_{q=1}^{q_{\max}} t_{Rn(i,q)} + \sum_{r=1}^{r_{\max}} t_{WTL(i,r)} + \sum_{u=1}^{u_{\max}} t_{WRRC(i,u)} + t_{Ctr}\right)\Big/ n, \quad (5)$$

where: $t_{S(i,p)}$ – service time of p-fold stop in i-fold simulation process [s]; p_{max} – number of stops at the analysed route section [–]; $t_{Rn(i,q)}$ – time travel on q-fold track section without any stoppages in i-fold simulation process [s]; q_{max} – number of track sections without any stoppages at the analysed route section [–]; $t_{WTL(i,r)}$ – waiting time before r-fold crossing with traffic lights in i-fold simulation process [s]; r_{max} – number of crossings with traffic lights at the analysed route section [–]; $t_{WRRC(i,u)}$ – waiting time before u-fold railway crossing in i-fold simulation process [s]; u_{max} – number of railway crossings at the analysed route section [–]; t_{Ctr} – service time of occupancy's control systems [s]; n – number of simulation processes [–].

To obtain fully reliable results in simulation, it was necessary to take into account also the time for entry into the single-track section, because the result of delays at other parts of tram network. It does not need to be equal to the moment of section release by the previous tram. There were taken into account the approaching, to a single-track sections tram, time of entry t_E. If a single-track section ended the whole tram route, distribution of delays between the tram appearances was characterized by the distribution of departure delays from the initial stop (Molecki 2008b):

$$F\left(d_E\right) = F\left(d_D\right) = \int_0^{d_D} \frac{1}{2\cdot t}\cdot e^{-\frac{\left(\ln(t)-3\right)^2}{1.28}}\,dt\,, \quad (6)$$

where: $F(d_E)$ – distribution function of appearance delay at the beginning of single-track section [–]; $F(d_D)$ –

distribution function of departure delay from the initial stop [–]; t – time [s]; d_E – appearance delay at the beginning of single-track section [s]; d_D – departure delay from the initial stop [s].

In the other cases the real-life distribution of appearance delays was taken into account:

$$t_E = t_{TT} + d_E\,, \tag{7}$$

where: d_E – appearance delay at the beginning of single-track section [s]; t_E – moment of appearance [s]; t_{TT} – timetable moment of appearance [s].

Comparing the moment of appearance of analyzed tram $t_{E(i)}$ with moment of single-track section releasing by previous tram $t_{A(i-1)}$, a moment of entry into the section was determined:

$$t_{D(i)} = \max\left(t_{E(i)}; t_{A(i-1)}\right), \tag{8}$$

where: $t_{D(i)}$ – i-fold tram moment of entry into the single-track section [s]; $t_{A(i-1)} = t_{D(i-1)} + t_{T(i-1)}$ [s]; $t_{T(i-1)}$ – (i-1)-fold tram single-track total travel time [s].

The values are shown in Fig. 3.

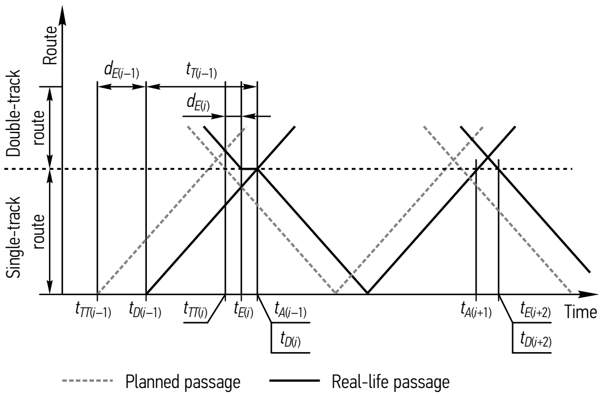

Fig. 3. Characteristic values appearing at calculating delays between trams at single-track route section

In addition, the calculation takes into account the fact that in two places on the network a system of packet traffic is also used on the basis of separate regulations. It consists of trams pulling in one direction, at an interval of about 1 minute, to the single-track section.

4.2. Calculations of Double-Track Sections Capacity, Crossroads with Traffic Lights, Junctions and Stops

Other procedures should be applied in the case of the double-track sections. Trams, similarly to road vehicles are moving on the principle of driving visibility. In the majority of track sections no section's occupancy control systems are being used, as it does on railways. In contrast to the road vehicles, not the principle of capacity based on the difference in speed is obligatory, but having a space greater than the braking distance (deceleration do not exceed 1.2 m/s^2). The distance depends on the speed: about 30 m at a speed of 20 km/h, up to about 200 m at a speed of 60 km/h. Nevertheless, the capacity of track sections is so high that it becomes negligible.

There were taken into account the capacity of any free flow of traffic limiters. These include:

- stops,
- junctions,
- crossings with traffic lights, other than strictly tram prioritizes.

For each of these elements the characteristics of capacity were created. The basis for their creation was the Monte-Carlo microsimulation based on previously determined distributions of occupation times of specific infrastructure elements. Determination subjected to the minimum interval between the courses, by which waiting time does not appear for more than 5% of the total number of courses. As the distribution of appearances a uniform distribution was used.

In case of stops their organization was also taken into account. Most of the stops on the network are single-stand (standard stops). A few, however, are double-stand (twin stops). Tram appearing to the unoccupied twin stop takes the first one of tram line independently. A tram appearing to stop on which the first stand is taken, takes the second one.

Examples of the characteristics for the stops are shown in Figs 4–7.

At the junctions in the tram track network, there are much wider limits, then both in rail and road vehicle traffic.

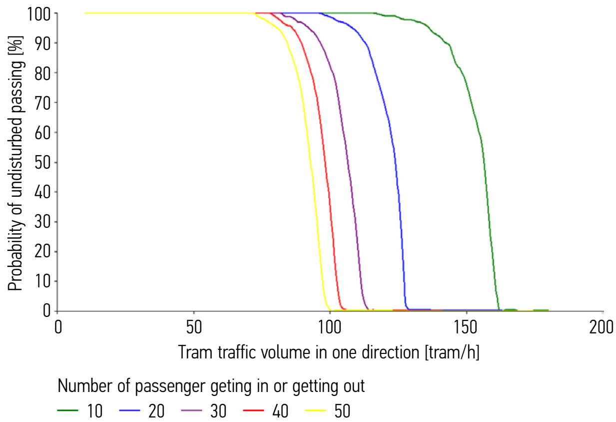

Fig. 4. Probability of undisturbed passing before standard stop

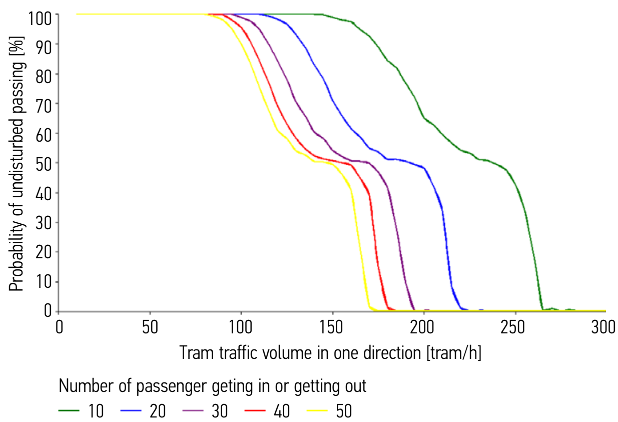

Fig. 5. Probability of undisturbed passing before twin stop

Greater deceptiveness of switch control than in rail traffic occurs as a result of:

- control by the tram driver, and not by one person – train dispatcher (Wilson, Norris 2006);
- reliable control systems of occupied junctions, leading to occasional, but necessary to take into account, the occurrences of switch moving (changing) under a passing tram (Fig. 8).

For the security reasons especially for passengers, almost no junction passing can be realized at the same moment. In case of the analyzed network there are two exceptions – tram roundabouts, where traffic is carried out in a similar way to automobile.

In the simulations, in addition to junctions' occupation time the existing directional traffic structure was also taken into account.

In case of crossings with traffic lights, the threshold of 95% probability of passing without halt cannot be determined, because it would require at least 95% of the share of green light for the tram (Fig. 9).

Taking into account the parameters of traffic lights and a minimum interval of traveling due to other smoothness limiters (stops on the track section and junctions ending sections etc.) was determined how many trams are able to drive through the crossing during a single cycle of traffic lights (Fig. 10). On this basis, the crossing capacity was determined.

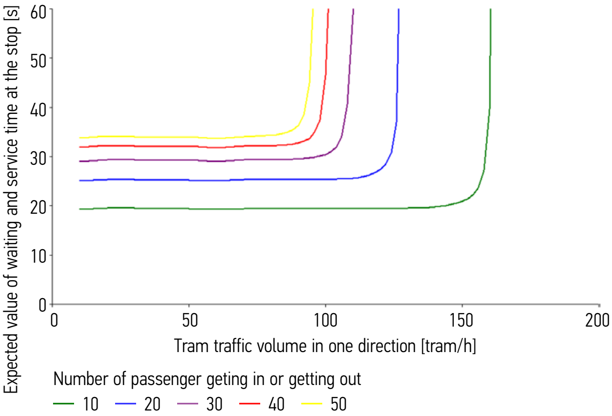

Fig. 6. Expected value of waiting and service time at the standard stop

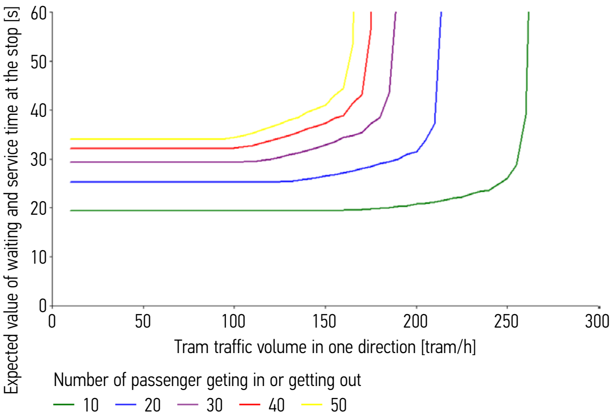

Fig. 7. Expected value of waiting and service time at the twin stop

Fig. 8. Tram derailment over a switch

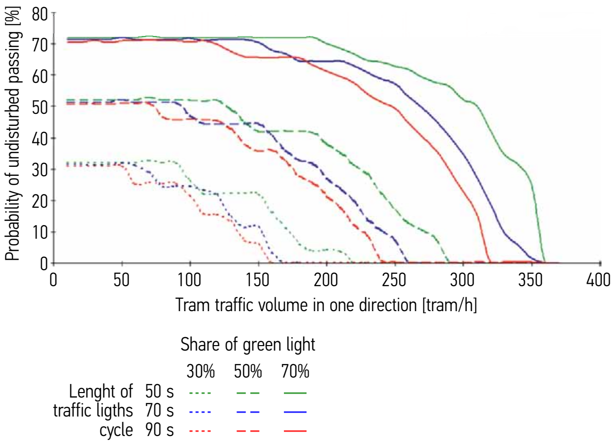

Fig. 9. Probability of undisturbed passing at the traffic lights

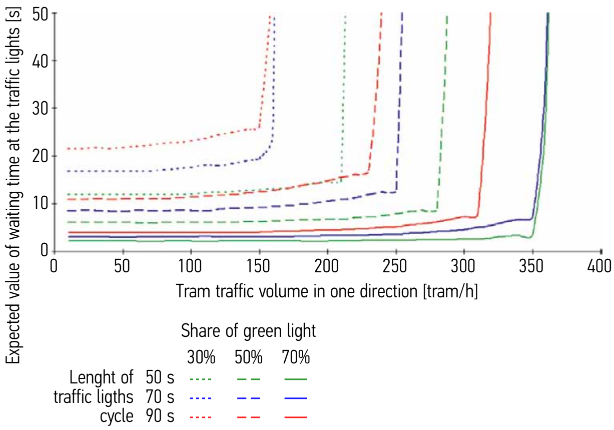

Fig. 10. Expected value of waiting time at the traffic lights

5. Capacity of Tram Network in Silesian Conurbation

For the purpose of capacity calculations, the tram network was divided into 74 sections. They were closed between junctions and turnings. In total, the capacity calculations of the tram network in Silesian Conurbation were taken into account:

- 131 crossings with traffic lights;
- 395 stops;
- 52 junctions;
- 51 single-track sections.

The calculated values of the tram network capacity are shown graphically in Fig. 11 (base variant – the current capacity) and Fig. 12 (capacity after the proposed modernization).

Following dynamic parameters of the rolling stock were assumed:

- maximal speed v_{max} = 70 [km/h];
- maximal acceleration a_r = 1.1 [m/s^2] (new and modernized cars), a_r = 0.8 [m/s^2] (base case);
- deceleration a_h = 1.2 [m/s^2] (new and modernized cars), a_h = 1.0 [m/s^2] (base case).

6. Conclusions

1. Properly carried out the capacity calculation may be an indication of timetable adjusting to preferences of the users. In the case of modernizing or building new sections they are a prelude in making decisions about public transport management.
2. Network capacity is crucial in terms of frequency of running trams, and therefore directly effects on the satisfaction of passengers (customers) and indirectly to many other parameters of traffic (travel time, comfort, traffic safety, etc.).
3. As a result of the calculation it can be noted that the tramway network in the Silesian Conurbation has strongly limited capacity (Fig. 11). After the planned modernization of the network the capacity should be significantly improved (Fig. 12).
4. By reducing number of capacity limiters such as crossings, junctions, etc. (by building collision-free junctions) – number of sections with a maximum capacity will increase significantly.
5. Special benefits can be obtained by constructing a second track, which was planned in one place (Katowice – Sosnowiec route). A wide range of improvement can be achieved by building an extensive system of tram prioritization at crossings with traffic lights.

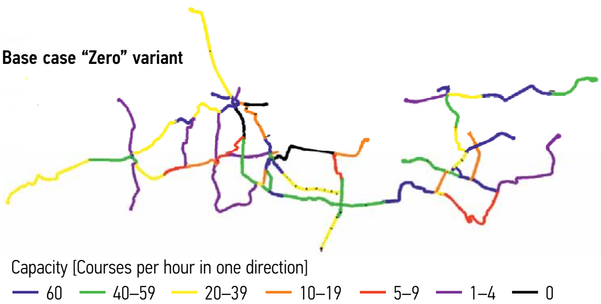

Fig. 11. Base case – the current capacity of tramway network

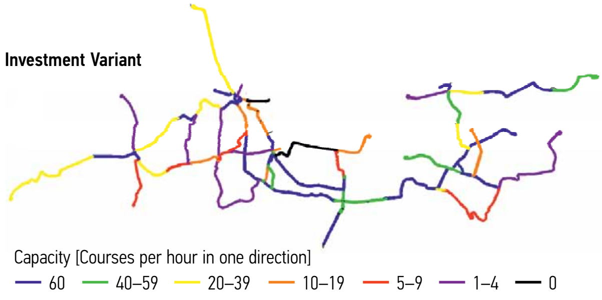

Fig. 12. Tramway network capacity after the proposed modernization

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