The Warsaw Traffic Study in 2015 along with the development of a traffic model

Synthesis

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1. Introduction

The main purpose of the study ordered by the Capital City of Warsaw under the name of "Warsaw Traffic Study along with the development of a traffic model" (WBR 2015) was to construe and calibrate a computer traffic model for Warsaw and the Warsaw Agglomeration, using the results of the WBR 2015 as well as data from other sources.

The project was implemented by a consortium composed of: PBS Sp. z o.o. as the consortium leader, the Cracow University of Technology and the Technical University of Warsaw.

In order to build the model, data from primary sources were used, namely study and measurements (made within WBR 2015) and data from secondary sources, such as statistical data and test and measurement results conducted by other entities.

The initial study within the WBR 2015 included:

- The study of transport behaviours of the residents of Warsaw
- Traffic measurements
- Measurements of the number of passengers in public transport vehicles
- The study of regional transportation bus passengers
- Measurements of traffic density and speed for updating the parameters of the volume-delay function
- Examination of freight traffic in the agglomeration

The use of data from secondary sources was based on among others, the analysis of the results of the "Public and Individual Traffic and Transport Study in the Masovian Voivodeship" as of 2014 (study on the level of a voivodeship), the results of the General Traffic Measurement 2015 and on data analysis of the Central Statistical Office, the Municipal Road Management Authority, Public Transport Management Authority and rail carriers.

The whole project "Warsaw Traffic Study 2015 along with the development of a traffic model" lasted from 12 February 2015 to 2 June 2016 and was implemented in four stages:

- PHASE I - preparation of study and measurements with the necessary arrangements.
- PHASE II - performance of study and measurements,
- PHASE II - analysis of study and measurements results,
- PHASE IV - elaboration of a computer traffic model
This document is a synthesis of the project, containing key information about individual studies and original measurements, together with their main results. Detailed information about the project is included in the reports of each of the project stages and published on the website http://transport.um.warszawa.pl/wbr2015.

2. Promotional activities supporting the study

The study and measurement phase was preceded by an information campaign, whose task was to inform Warsaw residents about the objectives and scope of the study performed as part of WBR 2015 and to encourage the residents to actively participate in the survey on travel behaviours, by meeting the interviewers and answering the questions asked by them. The goal of the campaign was to primarily reduce the number of refusals in the conversations with the interviewers.

Both, the Contractors and the Customer were involved in the preparation of the information campaign.

For the needs of the project, visual identification was created, namely a logotype and graphics were designed that were later used in all the materials related with the WBR 2015.

As part of the information campaign, in cooperation with the Social Communication Centre of the Capital City of Warsaw, an information leaflet and a poster were prepared, which a few days before the official launch of the study were placed in the means of public transport in Warsaw and in the seats of local authorities of the districts of Warsaw.
Spots broadcasted on the screens in public transport vehicles were also part of the information campaign, the same applied to subway stations, gyms, radio spots broadcasted by local radio stations. The Municipal Contact Centre 19115 was also involved in the information campaign, were respondents could confirm the identity of interviewers and get answers to the questions related to the study. On the website of the Office of Roads and Traffic System, a section with news and information regarding WBR 2015 was created. Information on the study were also provided on a Facebook profile.

3. The study of transport behaviours of the residents of Warsaw

Research method
The research was conducted on a sample of 17 000 residents of Warsaw, at the age of 6 years or more, visiting for this purpose 9 067 households.

Before the test, 2501 starting points were randomly selected, whose approximate locations are presented in Figure 3. From the starting points, using a "random route" further households were selected (every n-number). From one starting point, not more than four households were randomly selected.

Figure 3. Location of starting points.
The research sample obtained during the interviews, reflects the structure of Warsaw residents in terms of their place of residence, gender and age. Since during the interviews, the sample structure was not controlled due to the size of the household, and this feature affects directly transport behaviours, the data set was submitted to weighing procedure that adapted the sample structure in terms of the size of a household, to an analogical structure of analysed population. In addition, the structured weight allowed to make calculations for the entire studied population (i.e. sample extension).

The interviews in households lasted since 9 April to 27 June 2015. Long weekends were excluded, as well as the first week of the maturity exam (high-school exit exam), namely the days on which the number of travels and travel motivations differed from the standard travels on typical days.

**Main Study Results**

According to the assumption, the structure of the respondents reflected the population of Warsaw residents who are above 6 years of age, in terms of territory (district of residence), gender and age. All of the study results apply only to this group of residents.

In Warsaw, women outnumber men, as they constitute 54.5% of the population. From the age perspective, in Warsaw the largest age group are people between 26 to 64 years of age their share in the population is 61.5%. People aged 65 or over account for nearly 20% of the population, persons under 26 years of age represent a similar share.

Age structure directly reflects the structure of residents, in terms of their occupation, where pupils and students constitute 14.4%, retired persons or pensioners, almost 25%, while a dominating group are the working people (mostly outside of home), whose share is 56%.

From among 9067 surveyed households, the greatest share are single-person households (35.2%). The share of two-persons households is 30%, three-persons: 18.8%, while households consisting of four or more people account for 16% of the total number of households. The average observed number of people in the household is 2.2.

The primary objective of the study was to describe the trip that the residents of Warsaw perform on a typical working day. For this purpose, during the interview, so-called "diaries" were filled out, in which places visited on a previous day were recorded, as well as the times and way to these places were reached.

On a typical working day, nearly 82% of Warsaw residents performs at least one trip. The oldest are among the non-travelling group of people. Considering the main occupation of respondents, those who travel least are pensioners and persons classified as "others", i.e. mainly non-working and unemployed.
The overall mobility rate of Warsaw residents is 1.99 trips. This means that Warsaw residents perform nearly 3.35 million trips (3 348 336) every day. The vast majority of travels is performed with the use of means of transport, walks represent less than 20% of all trips performed during a day of travels.

The analysis of travel purposes shows that 44.1% of all displacements of Warsaw residents account for trips between home and work (in both directions), 11.1% are trips between home and place of study, 35.1% travel between home and other destinations, and 9.7% of trips are not associated with home.
Walked routes are less than one-fifth of all trips performed by Warsaw residents. Nearly half of displacements (46.8%) is performed with the use of public transport, less than one in three trips (31.7%) is done by car, and almost one in five (17.9%) on foot. 3.1% of travels are performed on bicycles.

Figure 6. Modal split.

Basis for the percentage split: all travels of the respondents.

After excluding from the analyses, travels performed entirely on foot, in the modal split, public transport travels represent 56.9%, 38.6% by passenger cars, and 3.8% are bicycle trips.

Figure 7. Modal split in the non-pedestrian trips.

Basis for the percentage split: all trips performed by respondents using means of public transport.

Three out of four non-pedestrian trips are performed without the need to change a vehicle. 57.2% of travels are made by public transport without changing a vehicle.
The morning traffic peak starts in Warsaw around 6 and lasts until 9 o'clock. At this time, approximately 930,000 trips start, which represents 27.8% of all trips during the day.

The afternoon peak period is longer, as it starts around 14 and lasts until 19, with the greatest intensity in 15-18 o'clock. Throughout the entire afternoon peak, 39.2% (1 311 thousand) trips commence, and in its most intense period - 28.2% (945 thousand) trips.

**Figure 8. Travel start time.**

*Basis for the percentage split: all travels of the respondents.*

Predominating trips among Warsaw residents are those that last not more than 30 minutes (61.1% of all trips), while the average travel time, declared by the respondents is 33 minutes.

**Figure 9. Distribution of travel times.**

*Basis for the percentage split: all travels of the respondents.*
The vast majority of trips performed by Warsaw residents are those of internal nature (95.5%), meaning such that begin and end in Warsaw. Travels, whose source or destination are located outside Warsaw, represent only 4.5% of all trips.

From among all the trips of Warsaw residents, 23.2% is associated with crossing the river. In total 59.6% of travels are performed on the left side of the river and 17.2% entirely on the right side. Approximately 775,000 travels a day are made through the Vistula River.

**Figure 10. Travel structure including trips across the Vistula River.**

*Basis for the percentage split: all travels of the respondents.*
Change of travel behaviours associated with the closure of the Łazienkowski Bridge

In February 2015 the Łazienkowski Bridge was closed for traffic, making it difficult to get through the Vistula River. The Contractor, in order to obtain the pest data for the creation of a travel model, decided to perform an additional study of a change of traffic behaviours resulting from these difficulties, despite the absence of such a requirement in the contract. The study was conducted with the residents of the area that was most strongly associated with the Łazienkowski Bridge (Figure 11). For this purpose, a transport model was used that was based on the results of previous WBR 2005 study. In this area, 1381 interviews were completed, questions about only three types of travels were asked: to work, to school and for other purposes.

Figure 11. The area covered by the study on the effects of the closure of the Łazienkowski Bridge for the change of transport behaviours.

Source: own analysis.

4 out of 10 residents of Warsaw living on the right bank, and working on the other side of the river, declared that after closing of the bridge, the way they reached to work changed, and some of them switched, for this purpose, from a passenger car, to public transport.
Figure 12. Mode of transport to work before and after the closing of the Łazienkowski Bridge.

Basis for the percentage split: persons who after the closing of the Łazienkowski Bridge changed the way of commuting to work (n=187).

4. Measurements of traffic intensity on the screens and cordons

1st Test method and measurement points

In the Warsaw Traffic Study in 2015, traffic intensity measurements were performed in designated sections of roads of different classes. The measurements were divided into: measurements on cordons (within the study area or a separate part thereof), on-screen measurements (on a particular line crossing the test area), and complementary measurements.

All the measurements were taken manually by trained observers who recorded the number of vehicles of designated types in each quarter.

Cordon measurements included 55 points on the outside cordon of Warsaw, set on the outlet roads from the city, on the border of Warsaw. The next cordons were marked by 67 points located on the roads crossing the external borders of the municipalities that make up the Warsaw Agglomeration and 41 points located in the downtown cordon, marked by the route of the existing and planned Downtown Ring Road.

The screen measurement was provided on the lines - screens, defining a given diameter of Warsaw. The first measurements covered 7 points (bridges) located on the screen of the Vistula River, without the Łazienkowski Bridge, excluded from operation. The second screen was the line designating the course of the Cross-City Railway Line that runs from east to west, where 30 measurement points were set.
Within the last group, the measurement was made in 15 points, in the area between the downtown, and the border of the Capital City of Warsaw. These were the points that enabled to determine traffic intensity of other important major roads and streets in the city that were not included in the above-described categories.

In addition, measurements of traffic density and speeds needed to determine the parameters of the volume-delay function (VDF) of a road section were conducted in 60 points. The section VDF interrelates the travel time by a given section with the traffic density, which means that the more intense the traffic, the longer the travel time. In this study, using a manual radar, speeds of various types were measured in free flow. In parallel with the speed measurements, in the same points, road traffic density was recorded. The collection of this data allowed us to determine the correlation between the speed of vehicles and road traffic density.

Due to the difficulties in the functioning of the transport network that took place during the measurement period (among others the closure of the Łazienkowski Baths, limiting the capacity of some roads), resulting in dynamic changes in travel behaviour and traffic volume, as well as technical constraints in manual measurements, some of the results caused doubts, primarily when calibrating the travel model. Therefore, in order to verify the WBR 2015 measurement results and calibrate the model, all available results from other measurements were used, such as those coming from, e.g. automatic measurements.

**Figure 13. Location traffic density measurement points.**

*Source: own analysis*
Using the results of the calibrated travel model, traffic flows on Warsaw and the downtown area cordons and on the screen of the Vistula River were specified. Daily, both cordons, Warsaw and downtown area, are crossed by around 1 million of passenger cars. Share of through traffic, which is not interested with agglomeration, equals 6.9% on Warsaw cordon and 2.5% on downtown area cordon. On Warsaw cordon around 550 thousand passengers cars make the flow related to agglomeration, since remaining traffic volume comes from outside the agglomeration. Screen of Vistula River is crossed daily by around 450 passenger cars in both directions.
5. Measurement of the number of passengers in public transport vehicles

Measurement of the number of passengers in the means of public transport lasted from 28 April to 11 June.

Passengers of buses and trams were counted on 2 cordons (central area and agglomeration) and 2 screens (the Vistula River and the Cross-City Railway Line) - in total, the measurement was carried out in 98 points.

Subway passengers were counted on 14 measurement sections on both subway lines, while railway passengers (SKM, WKD, KM) - on 17 sections. In addition, the measurement of persons getting on and off was carried out. This refers to the persons travelling in the trains of such providers, as: Intercity, Przewozy Regionalne on the following railway stations Central Warsaw, Warsaw East and Warsaw West.

All the measurements were carried out on typical weekdays (Tuesdays, Wednesdays, Thursdays). Depending on places, the counting of passengers took place in a system of 2 x 3 hours (between 6:00 and 9:00 and between 15:00 and 18:00) or in a 16-hour system (between 6:00 and 22:00). The number of passengers was determined by observation from outside. Observers were present in strictly defined points and assessed the degree of filling of vehicles in accordance with a previously elaborate pattern. Exceptions were the measurements of the number of passengers using the railways, where the passengers were counted on the train when travelling on the analysed section.

Figures 14-17 presents the results of the measurements of the number of passengers of public transport during peak traffic periods.
Figure 14. The number of passengers on buses and in trams, counted at the measurement points in the traffic peak hours.

![Bar chart showing the number of passengers on buses and in trams at different measurement points (Screen of Cross-City Line, Agglomeration Cordon, Centre Cordon, Vistula Screen) during 06:00-10:00 and 14:00-18:00.](chart1)

Source: own study based on the conducted measurements

Figure 15. The number of passengers getting on and off trains of Intercity and Przewozy Regionalne transportation companies.

![Line chart showing the number of passengers getting on and off trains at different stations (Central Warsaw, Warsaw East, Warsaw West) during 06:00-10:00 and 14:00-18:00.](chart2)

Source: own study based on the conducted measurements
Figure 16. The average number of persons in subway trains in peak traffic hours on the test sections LM1.

Source: own study based on the conducted measurements

Figure 17. The average number of persons in subway trains in peak traffic hours on the test sections LM2.

Source: own study based on the conducted measurements
6. The study of regional transportation bus passengers

The study was conducted based on direct interviews with the use of tablets on 16 stops of regional transport buses. 1,126 interviews were obtained in the study.

The sample was purposeful, persons leaving Warsaw in the afternoon were interviewed, and those who headed to towns located within the Mazovian Voivodeship, but outside of the municipalities of the Warsaw Agglomeration.

The study included mostly persons aged 19-49 (66% of respondents in total), persons above 50 years of age accounted for 20% of the sample, while those aged 15-18 years - 8%.

The respondents came to Warsaw primarily to work or school. The hour of arrival is connected with the purpose of the arrival - accumulation of arrivals to Warsaw took place between 7:00 and 7:59.

**Figure 18. Purpose of arrive to Warsaw.**

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>to work</td>
<td>59.1%</td>
</tr>
<tr>
<td>to school</td>
<td>14.8%</td>
</tr>
<tr>
<td>to university</td>
<td>10.0%</td>
</tr>
<tr>
<td>for shopping, for entertainment purposes</td>
<td>9.0%</td>
</tr>
<tr>
<td>in another purpose</td>
<td>7.1%</td>
</tr>
</tbody>
</table>

*Basis for the percentage split: persons living outside the Warsaw Agglomeration, n=944*

**Figure 19. Hour of arrival to Warsaw.**

<table>
<thead>
<tr>
<th>Hour of Arrival</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>before 6:00</td>
<td>5.4%</td>
</tr>
<tr>
<td>06:00-6:29</td>
<td>8.3%</td>
</tr>
<tr>
<td>06:30-6:59</td>
<td>11.4%</td>
</tr>
<tr>
<td>07:00-7:29</td>
<td>21.9%</td>
</tr>
<tr>
<td>07:30-7:59</td>
<td>20.0%</td>
</tr>
<tr>
<td>08:00-8:59</td>
<td>16.2%</td>
</tr>
<tr>
<td>09:00-9:59</td>
<td>5.4%</td>
</tr>
<tr>
<td>10:00-10:59</td>
<td>3.9%</td>
</tr>
<tr>
<td>11:00 or later</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

*Basis for the percentage split: persons living outside the Warsaw Agglomeration, n=944*
To move around Warsaw, persons arriving from outside of the agglomeration used primarily the means of public transport - it was used by 58%, 30% of respondents reached their destination on foot, and 11% were given a lift.

7. Freight Traffic Study

Freight Traffic Study in the agglomeration was conducted from 9 May to 27 June, 2015. The study involved 1,519 freight car drivers, who in their daily routes travel through the area of the Warsaw Agglomeration, or at least begin or end their routes in this area.

The average number of travels made by one vehicle was 7.59 for vehicles of the gross vehicle weight rating (GVWR) up to 3.5 t and 5.25 for the heavier vehicles.

The below graph provides information on the mobility of types of vehicles, depending on the industry to which the tested vehicles belong.

Figure 20. Mobility Irate for the types of vehicles (division: all vehicles; up to 3.5 t, above 3.5 t).

For lighter vehicles, the most frequent destinations were shopping and service destination, apart from major shopping centres. Almost half of the travels performed by lighter vehicles was performed for these purposes.

The aim of every third trip of the vehicles with a gross vehicle weight rating exceeding 3.5 tons was a construction site, which was also the most frequent destination for travels performed by vehicles from
the group of over 3.5 tons. Heavier vehicles more often than lighter vehicles perform journeys whose destination is an industrial plant, storage place or a warehouse.

Figure 21. Travel start time.

Basis for the percentage split: All travels undertaken by the surveyed drivers n=6952

The most travels begin between 7:00-7:59. In vehicles with a gross vehicle weight rating above 3.5 tons from 9:00 to 17:00 it oscillates between 8 and 10%. For lighter vehicles, the greater part of the travels takes place in the morning, and over time the percentage of travels drops.

Figure 22. The average length of journeys in kilometres, broken down by activity.

Sample: Travels, for which it was possible to determine the distance of n=6502
The average trip length for all surveyed vehicles is approx. 26 km. The average trip length of GVWR up to 3.5 t amounted to 16.1 km, while of heavier vehicles, 52.6 kilometres. Courier companies’ vehicles make the shortest trips. The average length of the travel of a courier company is almost 19 kilometres. Vehicles of companies that supply and service small commercial facilities also drive smaller distances; for them the average trip length is about 22 kilometres. Vehicles of companies that supply large commercial facilities and vehicles of companies of other kind of business activity drive an average of more than 30 kilometres in each trip.
8. Comparison of WBR results

Within the framework of WBR 2015 we made a comparative analysis of transport behaviours of Warsaw residents over the years. Residents’ mobility rates were compared, as well as the structure and average travel times for travels for the following years: 1980, 1993, 1998, 2005 and 2015. Analysis of the mobility rates results indicates that from 1993 to 2005 there has been a decreasing tendency in the number of travels performed and an increase in mobility over the last ten years. The observed increase is related to the strong urbanization of suburban areas. Migration from city centres to the areas of agglomeration result in an increase in travel demand.

**Figure 23. Comparison of mobility rates of Warsaw residents.**

![Graph showing mobility rates comparison](image)

*Source: own study based on archive study results*

The second area of comparisons covered the means of transport used when travelling. It has been observed that after reducing public transport trips in the late eighties and the beginning of the nineties, we can talk about a strong decline of the share of journeys performed with public transport, characteristic for the majority of the large cities in developed countries. This involves large expenditures aimed at improving public transport, its competitiveness under the congestion of the road system and an increase of environmental awareness. At the same time there has been a decrease in the number of pedestrian trips. The development of the automotive industry and the availability of public transport caused that city residents use the means of transport more often, especially over short distances, rather than going on foot. The above tendency is also visible in case of travels within Warsaw itself.
The analysis of not pedestrian trips shows that in the years 1993-2005 there was a slight increase in the number of trips by individual transport, and a simultaneous decrease in public transport. However, in the last ten years, the share of public transport has slightly decreased, at practically non-changed share of passenger cars. An increase in the use of bicycles was observed.
9. Internet study of travel behaviours

As part of the project "Warsaw Traffic Study along with the development of a traffic model" an on-line survey of transport behaviours of the residents was conducted. This study was designed to test whether the on-line survey that involved filling in a travel diary, it would be possible to obtain quality data comparable with the quality of data collected during the traditional analysis of transport behaviours, carried out during the visits of the interviewers in randomly selected households.

Having analysed the collected data, it was concluded that differences in key results of both studies were so significant that the results of on-line survey will not be used in the creation of the travel model.

Similarly, like before the implementation of the test of transport behaviours of Warsaw residents, the implementation of the on-line survey was preceded by an information campaign directed mainly to public transport users. As part of the promotional campaign, in the means of public transport in Warsaw posters and leaflets were placed as well as mass mailing was used to send out invitations to participate in the survey that was directed to the users of Warsaw Resident Cards. In addition, information banners of the study were placed on local websites of the Warsaw District Offices and on the Facebook profile of the Capital City of Warsaw.

During the study, 11130 surveys were collected. After the substantive control of the collected data, 6958 interviews were submitted for analysis.

Main Study Results

The structure of persons who took part in the on-line survey, differs significantly from the structure of the respondents in the primary (representative) study of the Warsaw Traffic Study 2015. The biggest differences are visible when comparing the age of the respondents: the average age of the WBR 2015 was 44 years, while the average age of the Internet users who filled out the questionnaire is 10 years younger than that. The largest group in the on-line survey consists of people aged 26-44, while the share of the youngest and the oldest people is negligible.

The professional situation of the respondents is translatable into the age structure of the respondents - 82% of persons taking part in the on-line survey are people working outside their home.

Respondents of the on-line survey are characterized by greater mobility. The mobility rate designated for participants of the on-line survey was 2.81, while in the representative study it amounted to 1.99.

The structure of trip purposes in the on-line survey differs from the structure observed in the representative study, which is due to differences in demographic and social structure of the respondents. As noted earlier, the mobility rate of the respondents in the on-line survey is higher, and thus the share of trips not associated with home is higher in trip purposes.
Distribution channels of invitations to participate in the on-line survey was largely determined by the structure of the means of transport used in travels. The on-line study recorded a much higher share of travels performed by public transport, and a smaller share of trips by car or on foot. The participants of the Internet-based study also more often declared the use of a bicycle in their trips.

In the on-line survey, the morning traffic peak was determined at precisely the same time as WBR 2015. The afternoon peak traffic is slightly shifted towards later hours, which is the result of a greater number of trips made without stopping at home. The activity of on-line study participants in the afternoon and evening travels is slightly higher than the activity of the respondents in the representative survey.
10. Transport model

A transport model is a mathematical description of interactions between the needs of the residents for commuting, creating the so-called transport demand and a transport network that offer a so-called transport supply. Most often, to transport models, a four-stage model is applied, whose name comes from the separation of a modelling process into four stages, as shown on Figure 29.

Figure 29. Structure of a four-stage travel model

A travel model for Warsaw and the Warsaw Agglomeration was developed according to the above scheme. In particular, three layers of the model were elaborate, corresponding to the: passenger traffic, meaning the individual transport (car, bicycle) and public transport (bus, tram, metro, light rail) and freight transport, like transporting goods by cargo trucks.

The area of the analysis, namely Warsaw and the Warsaw Agglomeration were divided into traffic analysis zones (Figure 30). A traffic analysis zone (TAZ) is a separate area characterized by a homogeneous form of spatial planning (e.g. residential buildings, industrial buildings, service areas) as well as the homogeneous transport behaviours of its residents. The Warsaw area was divided into 801 traffic analysis zone, while the municipalities of the Warsaw Agglomeration, into 95. Together, these 896 traffic analysis zone constitute the so-called internal areas. Additionally, external areas were taken into account that map inlets to the area of analysis of national, provincial, district and communal roads as well as railway lines.
The model assumes a simplification, that all the trips start and end in the traffic analysis zones. For each TAZ, explanatory variables are defined, namely the characteristics that describe a given area. These include parameters such as the number of inhabitants, number of jobs, number of places in schools, number of places at the universities, surface of large surface stores (LSS) and other. These variables are used to calculate the traffic-generating potentials, that is, how many people in a given area begin or end their trip (the first stage of a four-stage model). Moreover, they are used for forecasting. Knowing, that
in ten-year’s time, in the region a new housing estate, a factory, a shopping centre or office building will be built, it is possible to determine how much traffic this new facility will generate in the future.

Supply, namely a transport offer in a travel model will be the transport network consisting of sections designated for cars, trams, bicycles and trains. The transport network includes sections representing streets, bicycle paths and sections of the subway, tram and rail network as well as nodes mapping intersections or nodes of railway network. A street type in the model is characterized by two parameters: the free flow speed and capacity, which is defined as the maximum number of vehicles that can cross the section of the road in a time unit, for example 1000 vehicles/hour. If the traffic density (number of vehicles) on the section of the road exceeds its capacity, this causes traffic congestion. This description of a network is based on the functional and technical classification of roads and their technical parameters (e.g. the number and width of lanes). In addition, for each type of a section (type of street) in the model, a relevant volume delay function of a section is assigned. The type of junction has been mapped by the implementation of "penalties", for example for turning left at the intersection without traffic lights results in a greater loss of time than for vehicles, than driving straight ahead or turning right.

Public transport lines (buses, trams, subway, SKM, KM and WKD) are mapped based on actual routes and schedules. In case of sections used by means of rail transport (metro, tram, train), speed limits were introduced on the sections. While travel speeds, that is, average travel speeds taking into account stopping at bus stops and intersections, result from an introduced timetable. In case of the bicycle network, separate roads for bicycles and parametrized network elements were introduced, taking into account their attractiveness. In relation to freight traffic, tonnage restrictions were considered for trucks and an increased resistance of travel time was assumed on unattractive sections for heavy traffic. The condition of the transport network has been mapped as of 23 April 2015.
Figure 31. The transport network of the analysed area

The second key element of the travel model is transport demand, meaning the need to displace (persons and freight).

In the travel model of inhabitants, 18 trip purposes were identified that were connected with, among others, work, study (school, university), shopping or recreation. In every trip purpose, traffic-generating potentials were determined, as a product of explanatory variable and the coefficient determined based on survey results conducted in households. In case of trip purposes, where the beginning or the end of trips were connected with home (understood as a place of residence), mobility was a factor (the average number of trips performed in a day per one resident). For example, the mobility of working residents of Warsaw in the trip purpose home-work is 0.79. This means that 79% of persons in this group performs one trip from home to work during a day. Others working do not perform trips in this motivation, which may be due to holidays, sickness or home office. Travels from home to work end up in traffic analysis.
zones, where workplaces, proportional to their number, considering the impact of the distances from the travel source to the destination. A similar approach was used in all trip purposes.

In the four-stage model, entire flows are mapped, meaning the collective of travels for each route. Distance decay function is determined for the entire flow, which indicates how the distance to the travel destination affects its choice. For example, in mandatory trip purposes (e.g. work-related) residents are willing to accept longer distances to the destination, while in optional travels (e.g. shopping, recreation) the distances are much shorter. Figure 32 shows the comparison of the distribution of travels and that the share of longer trips in motivation home-work are much longer.

Figure 32. Distribution of the lengths of trips (according to WBR 2015)

The distance decay function is a characteristic feature of the spatial distribution gravity model of trips, which was used when creating a travel model. In this model, the number of travels between TAZ depends not only on their attractiveness (in terms of the number of commenced and ended trips), but also on the distance between them. Thus the greater the distance between the zones, the less trips will be performed. In addition, an important spatial element that affects the selection of a trip destination is the Vistula River. Each crossing of the Vistula is burdened with additional resistance, which was included in the spatial distribution of trips. Parameters of gravity model have been calculated for all the trip purposes and a high compatibility of the distribution of travel lengths between the model and the results of the survey was obtained.

The next step in the demand model is the modal split, which includes two steps. First, it is important to choose between walking and a motorized travel (by car or using means of public transport). The share of pedestrian trips depends on the distance between the beginning and the end of the trip. The farther
to the destination, the less eagerly walking trips are chosen. Based on survey results, it was assumed that all the trips shorter than 0.2 - 0.4 km (depending on the motivation) are made on foot. At the same time, also depending on the trip purpose, all the trips longer than 1.8 - 3.0 km are motorized, which means that they are performed by other means of transport, then by bike or on foot. The shape of the function of the share of trips by foot depends on travel motivations. Figure 33 shows an exemplary function in separating trips by foot.

Figure 33. Share of trips by foot depending on the length (according to WBR 2015)

If a trip by foot has been rejected, in the second stage, there is a choice from among other than pedestrian means of transport. In general, the issue boils down to a choice between a passenger car and public transport. Due to the very low, in general, share of travels at this stage, travels by motorcycle, bicycles and taxis were not contemplated, whereas bicycle traffic was contemplated as a separate layer. Factors that determine the choice of a means of transport include: owning a car, age, travel time from the source to the destination by car and by public transport, or the subway line on the route. Depending on the trip purposes, the impact of each factor will be different, or it will not occur at all. Nevertheless, in all the analysed trip purposes, the major factor that prevails in the choice of car, is the fact of having it. At the same time, which is quite obvious, real travel times by car and by public transport are an important criterion. An interesting observation is the effect of the presence of a subway line. The greater part of the route from the source to the destination includes the ability to use subway, the more eagerly public transport is chosen.

With regard to bicycle traffic, an original modal split was adopted, meaning the traffic-generating potentials of each area are determined in bicycle travels. In case of bicycle travels, travel motivations
were contemplated, for which formulas have been developed in order to determine traffic-generating potentials and spatial distribution.

In freight transport, two types of trucks were included: of the gross vehicle weight of less than 3.5 tons (the so-called delivery vans) and of the permissible mass weight above 3.5 tons. For both groups of vehicles, traffic-generating potentials were calculated, whose size depends on the number of job places in services and the surface of buildings of various purposes (e.g. retail, service, warehouse, production). Gravity model was used in the spatial distribution of freight transport. Modal split is determined at traffic generation level as a fixed share.

The last step is the distribution of trips in the transport network. In this process trips are carried out by cars are broken down onto the network according to the principle, according to which the driver selects the best route, taking into account other users and their impact on street congestion. In the case of trips performed by public transport, the trips are distributed among the route of public transport. The take-over degree by various means of public transport (bus, tram, subway, train) depends, among others, on the travel speed, service frequency and the proximity of stops. The distribution of freight traffic on the network takes into account the sections where heavy traffic is allowed and additional resistances on streets of lower classes. Matrices of bicycle trips have been distributed onto a network of bicycle paths, assuming that there are no capacity limitations of the cycling infrastructure, and cyclists always choose the shortest route from the source to the destination, taking into account the attractiveness of each section.

As a result of the distribution of travels onto the transport network, it is possible to obtain the intensity of traffic (Figure 34) and the passenger flow (Figure 35) on each section of the morning and afternoon peak hours.
Figure 34. Intensity of passenger cars traffic in the morning rush hour
Figure 35. Flows of passengers in the morning rush hour
The model prepared according to the above-described procedure requires calibration, meaning such an adjustment of certain parameters of the demand model or transport network, so that the results of the traffic distribution in the network were consistent with the results of traffic measurements and the passenger flow results. The results were compared, among other, on screens (e.g. crossings over the Vistula River, travels of the Cross-City Railway Line) and on cordons (e.g. inlet roads to the agglomeration, inlet roads to Warsaw). For the calibration purposes, many sources of measurements were used, including: measurements made within WBR 2015, automatic measurements performed by ZDM (the Municipal Road Management Authority) and the measurements of saturation of public transport vehicles and entrances to the subway station, performed by ZTM (Public Transport Management Authority).

The calibrated model for the existing scenario is the basis for the elaboration of traffic forecasts, which is an analysis of the condition of the transport system in the future. Traffic forecasts take into account the execution of planned investments (both road and in public transport), the increase in mobility of residents and the allocation of new areas for investment purposes (e.g. residential, commercial). An analysis of forecast variants allows to rationally plan the development of the city transportation system and to evaluate tendencies in spatial planning.

A travel model is a powerful mathematical tool that allows to quickly analyse the effects of changes in the transport network and in the spatial planning of the city, such as: the construction of a new road, or the closure of an existing one, launching of a re-routing of an existing map of public transport lines, construction of a new housing estate or a shopping centre.
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