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# MODELLING OF EXPECTED TRAFFIC SMOOTHNESS IN URBAN TRANSPORTATION SYSTEMS FOR ITS SOLUTIONS

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***Abstract:****In urban networks, with dense traffic flows and a high risk of the disruption (even in the form of a short queue of vehicles) the probability of occurrence of such a situation (disruption and queue) is a better measure of the probabilistic description of the capacity constraints than the expected waiting time in the queue, because the probability takes into account the risk of delay in the traffic flow from the point of view of the person that plans a trip. The functions of expected smoothness of the traffic flows in the elementary nodes and the expected waiting time in the queue for different packages of ITS services have been presented in the mathematical forms.*

***Key words:*** *traffic smoothness theory, ITS modelling, modelling transport in urban area*

## 1. Introduction

Considering the problems of traffic congestion in systematic way one can distinguish two principal areas of possible actions: the area of travel and transport demand management and the area of supply—understood as the transportation system—and the use of packages of ITS services (Karoń, Żochowska and Sobota, 2011; Żochowska and Karoń, 2016). These two areas permeate each other. Currently, the ITS services also provide a useful tool for transport demand management. Therefore effective congestion management should cover not only changes in the transportation system of the city and its surroundings, but also an influence – in an appropriate way – on decisions of its users in terms of the way and time of planned trip. The wide variation in the pattern of the users of the transportation system and of the purposes of their trips requires the use of various packages of ITS services. The ITS services satisfy with this enormous role in shaping the desired travel behaviours.

## 2. Transportation models and packages of ITS services for urban transportation systems

Modelling of transportation systems provides practical solutions for traffic management and control within the structures of ITS. Transportation models are practically used to (Karoń, 2013; Szarata, 2014; Osorio and Bierlaire, 2009, Federal Highway Administration, 2004-2010; Żochowska 2014a, Żochowska 2014b):

- evaluate, simulate or optimise the operation of transportation facilities and systems;
- model the existing operations and predict likely outcomes of proposed design options;
- evaluate various analytical contexts, including planning, design, and operational/construction projects,
- model the passengers streams in public transportation systems (Chmielewski and Szczuraszek, 2004; Izdebski, 2014) and cargo streams in transportation systems (Horbachov and Svichynskyi, 2014; Jacyna, 1999; Szczepański et al., 2014; Wasiak, 2011).
- model logistic systems (Wasiak, 2007; Wasiak, 2009) with supply chains (Bieniek, 2004; Pyza 2008; Pyza 2009; Pyza, 2011, Wolfenburg, 2014).
- measure and evaluate pollutant and noise emission by passengers and heavy-duty vehicles (Ambroziak et al., 2014; Jacyna and Merkisz, 2014; Merkisz et al. 2014; Merkisz-Guranowska and Pielecha, 2014),
- develop sustainable (Jacyna et al., 2014) and proecological transportation system (Jacyna-Gołda et al., 2014),
- model of economical assessment of implementation proecological vehicle's drive –

electric drive – for conception of smart cities (Janecki and Karoń, 2014).

The most popular travel demand models – four-stages transportation models – allow forecasting future travel demand based on current conditions and future projections of household and employment characteristics (Cascetta, 2009; Grant-Muller and Laird, 2006).

Such models take into consideration the destination choice, mode choice, time-of-day travel choice, and route choice, and the representation of traffic flow in the transportation network (Żochowska, 2014d). Unfortunately, these models are poor to evaluate impacts of ITS systems on transportation systems, because of limited capabilities to estimate changes in operational characteristics (such as flows, speed, density, delay, and queuing) in an accurate manner and of poor representation of the dynamic nature of traffic.

Better choice for ITS impact evaluation are macro-, meso-and/or microscopic simulation models. These models may take into consideration (Federal Highway Administration, 2004-2010):

- the fundamental diagram with deterministic relationships of the flow, mean speed, and density of the traffic streams (Żochowska and Sobota, 2014),
- the movement of individual vehicle types and driver behaviours. Furthermore, traffic operational characteristics of each vehicle may be influenced by vertical grade, horizontal curvature, and super elevation,
- combination of the properties of both microscopic and macroscopic simulation models.

Example of traffic flows analysis with microscopic simulation model for technical variants to improve traffic conditions on the weaving section of main road in urban agglomeration has been presented in (Wnuk and Karoń, 2014). The technical variants with ramp metering system has been implemented in microscopic simulation model too.

For all these models ITS systems are sources of data (with problems of big data exploration and processing in real time). The ITS services (e.g. sensors and recorders to measure the volume of traffic, availability of parking spaces, actual transit times, arrival and departure from the stops, etc.) provide technological possibilities of acquiring the data. Technologies that ensure to deliver data to users include Internet, LAN, WAN, telephones, wired and wireless technologies, including mobile phones and PDA mobile devices, information kiosks, variable message signs on roads, streets, bus stops, car parks and on-board in vehicles navigation systems (Żochowska and Karoń, 2016). And also ITS systems need transportation models for their full functionality (see Fig. 1 – functional integration of ITS systems on the fields of activities and transportation systems in urban area).

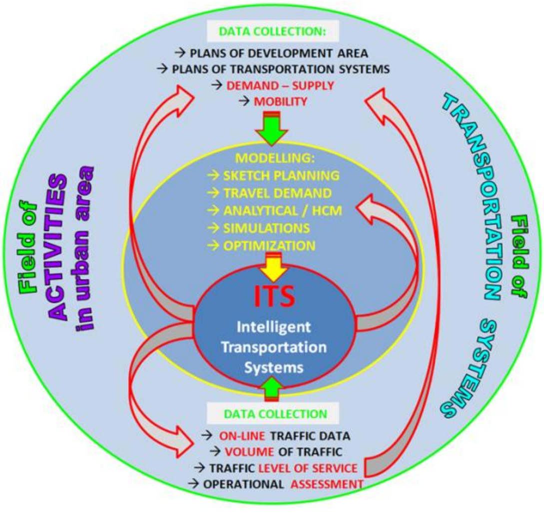


Fig. 1. Functional integration of ITS systems on the fields of activities and transportation systems (Karoń and Mikulski, 2011b)

Each place of disruption of traffic flow smoothness in the transportation network may be represented as an elementary node (Woch, 1999; Woch 2004).Therefore, for modelling of expected traffic smoothness that takes into account places of traffic disruption in urban transportation systems the following description is required (Ambroziak and Jacyna, 2002; Ambroziak and Jacyna, 2003; Jacyna, 2009; Żochowska and Karoń, 2016):

$$\boldsymbol{I} = \{1, \dots, i, \dots, \bar{I}\}, \tag{1}$$
$$\boldsymbol{J} = \{1, \dots, j, \dots, \bar{J}\}, \tag{2}$$

where:
$\boldsymbol{I}$ - the set of numbers of traffic flows passing through the elements (links and nodes) of analyzed transportation network; $\bar{I}$ is the size of $\boldsymbol{I}$,
$\boldsymbol{J}$ - the set of numbers of elementary nodes; $\bar{J}$ is the size of $\boldsymbol{J}$,

Moreover following subsets may be defined:

$$\boldsymbol{I}^j = \{i: \alpha(i,j) = 1,\ i \in \boldsymbol{I}\}, \quad j = 1, \dots, \bar{J}, \tag{3}$$
$$\boldsymbol{J}_i = \{j: \alpha(i,j) = 1,\ j \in \boldsymbol{J}\}, \quad i = 1, \dots, \bar{I} \tag{4}$$

and following mapping:

$$\alpha: \boldsymbol{I} \times \boldsymbol{J} \rightarrow \{0,1\}, \tag{5}$$

where:
$\boldsymbol{I}^j$ - the subset of $\boldsymbol{I}$ containing numbers of traffic flows passing through the $j$-th elementary node,
$\boldsymbol{J}_i$- the subset of $\boldsymbol{J}$ containing the numbers of elementary nodes, through which the $i$-th traffic flow passes,
$\alpha(i,j)$- quantity $\alpha(i,j) = 1$ if and only if the $i$-th traffic flow passes through the $j$-th elementary node, otherwise $\alpha(i,j) = 0$.

The smooth traffic flow, which refers to the stochastically stabilized flow (i.e. flow without disruption, that prevents the acceptance of a specific probability distribution of the headways), in the queuing model with moving buffer (Heidemann, 1996), may be described using the maximum density $k_{\text{smooth}}$ referring to the smooth flow. In smooth flow vehicles ride with the speed $v_{\text{smooth}}$ with no additional delays (no waiting time), and with the same intensity $q$ of vehicles by all minimal distances ${}^{1}/_{k_{\text{jam}}}$ that are components of path of the smooth flow (Żochowska, 2014d):

$$q = k_{\text{smooth}} \cdot v_{\text{smooth}}. \tag{6}$$

The density $k_{\text{jam}}$ stands for the jam density and therefore ${}^{1}/_{k_{\text{jam}}}$ is length of elementary segments of the road, as described for example in the queuing model with moving buffer (Heidemann, 1996). Thus $k_{\text{smooth}}$ is the maximal number of vehicles forming smooth flow.
The gap between vehicles in smooth traffic flow—taking place on the road consisting of distances ${}^{1}/_{k_{\text{smooth}}}$—is dependent on the expected (mean) speed $v_{\text{smooth}}$ of free traffic flow and shall take into consideration the safety distance (safe gap), mapped by shifting the exponential distribution of headways on the road.
Such mapping is also related to the fact that in description of the traffic flows of high density the small variances of gaps are taken into account. In addition, in dense traffic flows a minimal safety distance (safe gap) is relatively small, with the result that the probability of disruption—in the form of sudden deceleration (stop) of vehicles—increases. Therefore, the probability (risk) of the formation of queues of vehicles is growing. Taking into account the possibility of the formation of queues of vehicles during such disruption, the necessary and sufficient condition of smooth traffic flow may be written as (Żochowska and Karoń, 2016):

$$\mathrm{E}\big(Lp(\boldsymbol{Q})\big) \leq 1, \tag{7}$$

which means that in the smooth traffic flow with intensity $\boldsymbol{Q}$ the expected length of the queue, expressed as the number of vehicles $Lp(\boldsymbol{Q})$, that occur at the minimal distance ${}^{1}/_{k_{\text{smooth}}}$, is not greater than one vehicle. The probabilistic description of the forming queues and their impact on the smoothness of traffic flows passing through the network, and thus on the efficiency of the traveling of vehicles in dense traffic flows, may be used to search for the optimal intensity of traffic flows on the sections of the road.

Intelligent Transportation Systems (ITS) are interrelated systems that work together to deliver transportation ITS services. An ITS architecture defines a framework within which ITS systems may be built, and the information that is exchanged between elements of ITS systems, as (Architecture Development Team, 2012):

- the functions that are required for ITS,
- the physical entities or subsystems where these functions reside (e.g., the field or the vehicle),
- the information flows and data flows that connect these functions and physical subsystems together into an integrated system.

Mentioning above ITS systems offer the potential to improve smoothness of traffic flows, by means of the user services grouped in service packages.

Therefore, for modelling of expected traffic smoothness that takes into account ITS user services and services packages the following description of ITS systems is required. The set of numbers of packages of the ITS services (tab. 1) has been defined as follow (Żochowska and Karoń, 2016):

$$\boldsymbol{SP} = \{1, \dots, sp, sp', \dots, \overline{SP}\}, \tag{8}$$

where:

$\boldsymbol{SP}$ - set of the number of packages of ITS services that may be implemented in the transportation network; $\overline{SP}$ is the size of the set $\boldsymbol{SP}$.

The choice of each package of ITS services results in a specific traffic arrangement described by traffic assignment in the transportation network – using capacity restraint function describing current travel time in loaded/congested network.

In order to describe the fundamental diagram of traffic flow for each of the packages of ITS services, it was assumed that on the Cartesian product $\boldsymbol{I} \times \boldsymbol{J} \times \boldsymbol{SP}$ the specific mappings $v$ (speed), $k$ (density) and $q$ (intensity), that transforms components of this product into the elements of the set $\mathbb{R}^+ \cup \{0\}$, is given, i.e.:

$$v: \boldsymbol{I} \times \boldsymbol{J} \times \boldsymbol{SP} \to \mathbb{R}^+ \cup \{0\}, \tag{9}$$

$$k: \boldsymbol{I} \times \boldsymbol{J} \times \boldsymbol{SP} \to \mathbb{R}^+ \cup \{0\}, \tag{10}$$

$$q: \boldsymbol{I} \times \boldsymbol{J} \times \boldsymbol{SP} \to \mathbb{R}^+ \cup \{0\}. \tag{11}$$

For individual $sp$-th package of the ITS services the traffic conditions described by the fundamental characteristics in $j$-th elementary node may be presented in the form of vectors (Żochowska and Karoń, 2016):

$$\boldsymbol{V}^j(sp) = \langle v_i^j(sp) : i \in \boldsymbol{I}^j \rangle, \quad j = 1, \dots, \bar{J}, sp = 1, \dots, \overline{SP}, \tag{12}$$

$$\boldsymbol{K}^j(sp) = \langle k_i^j(sp) : i \in \boldsymbol{I}^j \rangle, \quad j = 1, \dots, \bar{J}, sp = 1, \dots, \overline{SP}, \tag{13}$$

$$\boldsymbol{Q}^j(sp) = \langle q_i^j(sp) : i \in \boldsymbol{I}^j \rangle, \quad j = 1, \dots, \bar{J}, sp = 1, \dots, \overline{SP}, \tag{14}$$

where:

$\boldsymbol{V}^j(sp)$ is the set of speed of traffic flows; element of this set $v(i,j,sp) \equiv v_i^j(sp) \in \mathbb{R}^+ \cup \{0\}$ has an interpretation of speed of the $i$-th traffic flow passing through the $j$-th elementary node by applying $sp$-th package of the ITS services,

$\boldsymbol{K}^j(sp)$ is the set of density of traffic flows; element of this set $k(i,j,sp) \equiv k_i^j(sp) \in \mathbb{R}^+ \cup \{0\}$ has an interpretation of density of the $i$-th traffic flow in the $j$-th elementary node by applying $sp$-th package of the ITS services,

$\boldsymbol{Q}^j(sp)$ is the set of intensity of traffic flows; element of this set $q(i,j,sp) \equiv q_i^j(sp) \in \mathbb{R}^+ \cup \{0\}$ has an interpretation of intensity of the $i$-th traffic flow passing through the $j$-th elementary node by applying $sp$-th package of the ITS services.

The values of $v_i^j(sp)$, $k_i^j(sp)$ and $q_i^j(sp)$ for $i$-th traffic flow which does not pass through the $j$-th elementary node by applying $sp$-th package of the ITS services are zero.

## 3. Expected smoothness of traffic flows

The average delays—which correspond to the traffic flow passing through the elements of transportation network—are closely dependent on the speed, density, and intensity both of the analyzed traffic flow and of other flows in the network - flows interact at each elementary node. It should also be noted that the values of these three fundamental characteristics of traffic flow for each elementary node may be different (Żochowska 2011, Żochowska 2012).

Average delay $w_i^j(sp)$ which corresponds to the passing of the $i$-th traffic flow through any $j$-th elementary node by applying $sp$-th package of the ITS services, is dependent on traffic conditions in the node (Żochowska and Karoń, 2016), i.e.:

$$w_i^j(sp) = w_i^j\left(\boldsymbol{Q}^j(sp)\right),$$
$$\forall i \in \boldsymbol{I},\ \forall j \in \boldsymbol{J},\ \forall sp \in \boldsymbol{SP}. \quad (15)$$

In turn, the average delay $w_i(\boldsymbol{Q}(sp))$ corresponding to passing of the $i$-th traffic flow through the transportation network are equal to the total delay in all elementary nodes of the network, which may be written as:

$$w_i(\boldsymbol{Q}(sp)) = \sum_{j \in \boldsymbol{J}_i} w_i^j\left(\boldsymbol{Q}^j(sp)\right),$$
$$i = 1, \dots, \bar{I}, \quad sp = 1, \dots, \overline{SP}, \quad (16)$$

where $\boldsymbol{Q}(sp)$ is a matrix containing the values of traffic intensity for all traffic flows in all elementary nodes of the transportation network by applying $sp$-th package of the ITS services, i.e.:

$$\boldsymbol{Q}(sp) = \left[q_i^j(sp):\ i \in \boldsymbol{I},\ \ j \in \boldsymbol{J}\right],$$
$$sp = 1, \dots, \overline{SP}. \quad (17)$$

Determination of the relationship between the smoothness and the intensity of traffic flows leads to the optimization problem of traffic assignment in the transportation network. According to Woch (2004) the optimal traffic assignment in the transportation network is conditioned by optimization of traffic assignment in each elementary node of the network. Only the analysis of elementary traffic conflicts in the nodes provides an accurate assessment of the smoothness of traffic flows.

Disruptions of the smoothness of the traffic flows usually occur in the critical nodes. So, on the one hand disturbed traffic flow indicates the location of the greatest potential benefits from the improvement of traffic assignment (see for example Wnuk and Karoń, 2014), and on the other – the structure of the queues in the complex critical nodes maps the reserve capacity in their elementary nodes. This allows for such selection of the package of the ITS services, that leads to the optimal variant of the traffic assignment.

In the optimization of the traffic flows in the transportation network, the fundamental measure of the smoothness theory of traffic flows—a function of the expected smoothness of traffic flows—may be taken as a function of the criterion (Woch, 2004), i.e.:

$$F_i^j\left(Q^j(sp)\right) = \left[1 - p_i^j\left(Q^j(sp)\right)\right] \cdot q_i^j(sp),$$
$$i = 1, \dots, \bar{I}, \quad j = 1, \dots, \bar{J},\ \ sp = 1, \dots, \overline{SP}, \quad (18)$$

where:

$F_i^j\left(Q^j(sp)\right)$ – the function of the expected smoothness of the $i$-th traffic flow in the $j$-th elementary node, assuming the intensities of traffic flows are consistent with the vector $Q^j(sp)$,

$p_i^j\left(Q^j(sp)\right)$ – the probability of the queue in the $i$-th traffic flow in the $j$-th elementary node, assuming the intensities of traffic flows are consistent with the vector $Q^j(sp)$.

By using $sp$-th package of the ITS services for the $i$-th traffic flow, the searching the optimal its intensity $q_{\mathrm{smooth}i}(sp)$, comes down to finding the maximum value for the function of the expected smoothness $F_i^j\left(Q^j(sp)\right)$ for each elementary nodes, through which the $i$-th traffic flow passes, and then to determine the optimum intensity for this flow over the entire path in the transportation network (Żochowska and Karoń, 2016). This value will be the optimal intensity $q_{\mathrm{smooth}i}(sp)$ for the $i$-th traffic flow.

The optimization problem may be written as:

$$q_{\mathrm{smooth}i}(sp) = \min_{j \in J_i}\{q_{\mathrm{smooth}i}^j(sp)\}, \quad (19)$$

where:

$$q_{\mathrm{smooth}i}^j(sp):$$
$$F_i^j\left(q_{\mathrm{smooth}i}^j(sp)\right) = \max_{q_i^j(sp) \in Q(sp)}\left\{F_i^j\left(q_i^j(sp)\right)\right\},$$
$$i = 1, \dots, \bar{I}, \quad j = 1, \dots, \bar{J},\ \ sp = 1, \dots, \overline{SP}, \quad (20)$$

where:

$q_{\mathrm{smooth}i}(sp)$ - the optimal intensity for the $i$-th traffic flow passing through the network, assuming the intensities of traffic flows are consistent with the vector $\boldsymbol{Q}(sp)$,

$q_{\mathrm{smooth}i}^j(sp)$ - the optimal intensity for the $i$-th traffic flow passing through the $j$-th elementary node, assuming the intensities of traffic flows are consistent with the vector $\boldsymbol{Q}(sp)$,

$F_i^j\left(q_{\mathrm{smooth}i}^j(sp)\right)$ - the function of the expected smoothness with the optimal intensity $q_{\mathrm{smooth}i}^j(sp)$ of the $i$-th traffic flow in the $j$-th elementary node, assuming the intensities of traffic flows are consistent with the vector $\boldsymbol{Q}(sp)$.

The functions of the expected smoothness $F_i^j\left(\boldsymbol{Q}^j(sp)\right)$ of the $i$-th traffic flow in the $j$-th elementary node for various packages $sp$, $sp'$, …, $sp^*$ of the ITS services and different capacities $q_i^{*j}(sp)$, $q_i^{*j}(sp')$, **…**, $q_i^{*j}(sp^*)$ as well as different intensities $q_{\text{smooth}i}^j(sp)$**,** $q_{\text{smooth}i}^j(sp')$, **…**, $q_{\text{smooth}i}^j(sp^*)$ optimal in terms of smoothness of traffic flow, that correspond to these packages, have been presented in the Fig. 2.

For different traffic assignment in elementary node, there are different functions of the expected smoothness of traffic flows, that are determined on the basis of changes in function of the probability of disruption $p_i^j\left(\boldsymbol{Q}^j(sp)\right)$, $p_i^j\left(\boldsymbol{Q}^j(sp')\right)$, ..., (these are conditional probabilities of waiting in the queue of vehicles) and of the unconditional probability $p_i^j\left(\boldsymbol{Q}^j(sp^*)\right)$. The maximum value of the conditional capacity occurs in the absence of interaction with the other flows and is called unconditional capacity $q_i^{*j}(sp^*)$ of the $j$-th elementary node for the $i$-th traffic flow, which corresponds to the unconditional capacity $p_i^j\left(\boldsymbol{Q}^j(sp^*)\right)$.

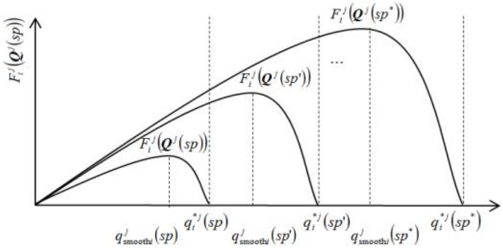


Fig. 2. The functions of the expected smoothness of traffic flows for various packages of the ITS services (Woch, 1999; Woch, 2004; Żochowska and Karoń, 2016)

The permanent small disruptions are the results of very high density of traffic flow. They are caused by gaps between vehicles that are close to minimal distances (minimal gaps) - the variation of the gaps is equal to or close to zero. In such situation the high probability (risk) of the formation of queues is caused by delayed reaction of human-vehicle system.

The probability of disruption, resulting in the queues of vehicles, increases nonlinearly with increasing of the intensity and of the density of the traffic flows. In a similar way, the waiting time in the queue of vehicles is increasing, if such disruption has occurred. In addition, the smaller the conditional capacity is—and thus the smaller optimal intensity, due to the low level of smoothness of traffic flows—the faster the waiting time in the queue due to disruption is growing.

Therefore, the optimal intensities for the individual network elements are not equal to their capacities - they are smaller. This follows from the fact that the intensity of the traffic flow equal capacity of the node occurs when all vehicles are moving in the states close to the saturation states with very limited levels of service, and thus the function of the expected smoothness of traffic flow reaches zero - no vehicle is moving freely. Traffic flow with the intensity equal to (or close to) capacity is characterized by the conditional capacities $q_i^{*j}(sp)$, $q_i^{*j}(sp')$, ..., and unconditional capacity $q_i^{*j}(sp^*)$. All of them depend on the variants of traffic assignments $\boldsymbol{Q}^j(sp)$, $\boldsymbol{Q}^j(sp')$, ..., $\boldsymbol{Q}^j(sp^*)$ for the remaining traffic flows.

Moreover, the expected delays for the $i$-th traffic flow in the $j$-th elementary node are also the conditional values $w_i^j\left(\boldsymbol{Q}^j(sp)\right)$, i.e. dependent on the variants of traffic assignment for other flows in the network. The functions of expected delays for the $i$-th traffic flow in the $j$-th elementary node in form of the expected waiting time $w_i^j\left(\boldsymbol{Q}^j(sp)\right)$ in the queue for different packages of ITS services $sp$, $sp'$, …, $sp^*$ and the appropriate capacities $q_i^{*j}(sp)$**,** $q_i^{*j}(sp')$**, …,** $q_i^{*j}(sp^*)$ have been presented in the Fig. 3.

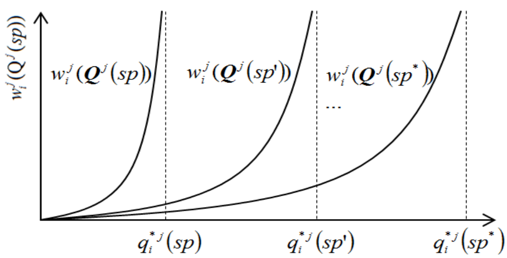


Fig. 3. The functions of the expected delays of traffic flows for various packages of the ITS services (Woch, 1999; Woch, 2004; Żochowska and Karoń, 2016)

Described above approach takes into account the specific traffic control in the network, which is the result of proper selection of packages of the ITS services. The specific traffic assignment is the result of this selection.

## 4. Practical aspects and problems of ITS implementation – example in Poland

The example of analysis of traffic flows disruption in the complex node of urban transportation network (Wnuk and Karoń, 2014) presents changes in disruption of traffic flows depending on various configuration of weaving multilane section. The location of analyzed weaving section in Katowice city – capital of Upper-Silesian Agglomeration, taking into account traffic assignment, has been presented in the Fig. 4.

The complexity of weaving interactions of traffic flows is as follows. Movements (1-7), (1-8) and (2-5), (2-6) does not require a lane change. Movements (1-6), (2-7) require one lane change, whereas movements (1-5), (2-8) require two lane changes. Movement (2-8) operates functionally as a weavingflow with vehicles ride from right-hand on-ramp to left-hand off-ramp. Ramp-to-ramp vehicles must cross all lanes of the weaving section to execute their desired maneuver. Movement (1-5) operate functionally as a weaving flows with vehicles ride from on-lane to off-ramp. The complexity of flows weaving required use of microsimulation modelling for traffic smoothness. Three different variants of traffic weaving have been evaluated. The most effective variant is adjustment of weaving section configuration and change of interchange geometry (compare Fig. 4 and Fig. 5). This improvements decrease number of merge and diverge points by decrease number of points of origin-destination (O-D) intersections (see Fig. 6). It leads to increase smoothness of traffic flows and increase level of service (LOS).

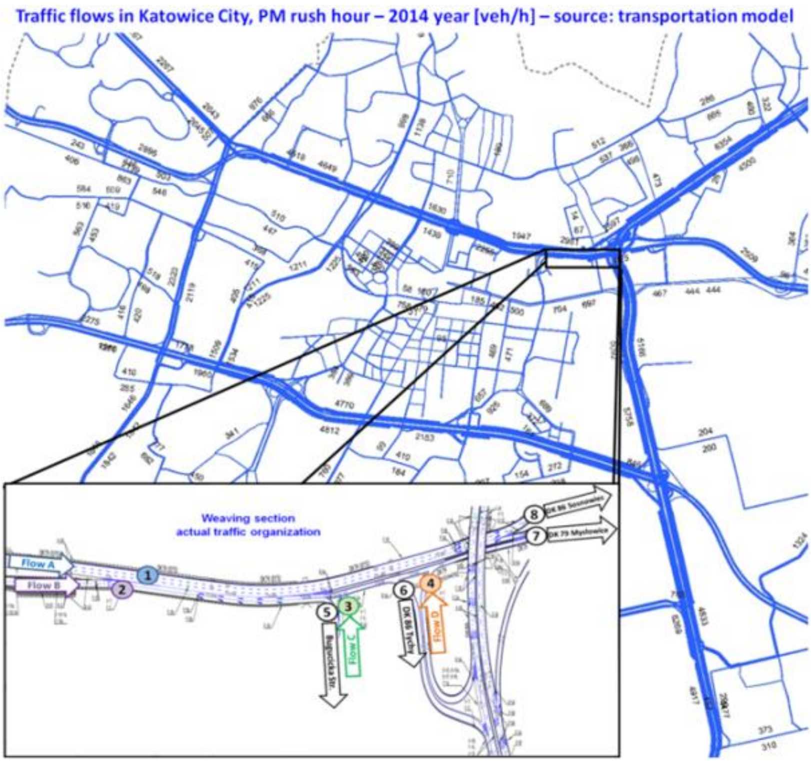


Fig. 4. Location of analyzed weaving section in transportation network – traffic flows estimated from urban transportation model for PM rush hour

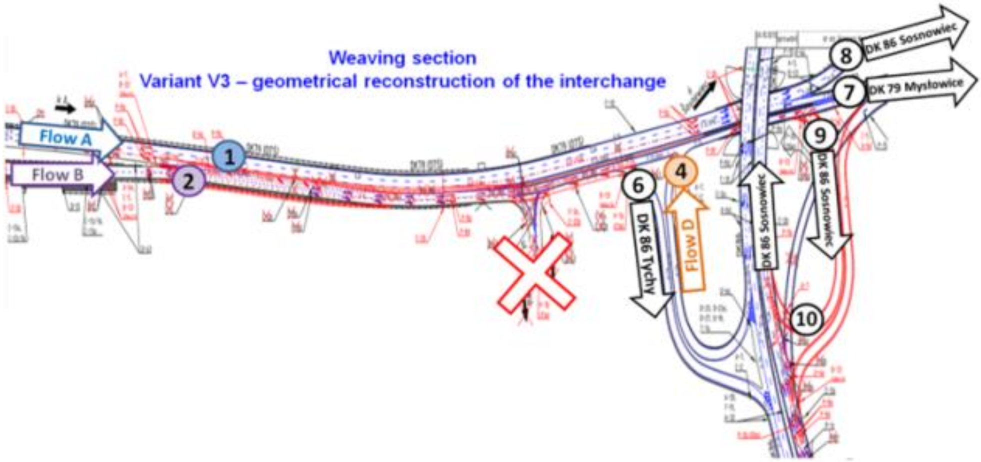


Fig. 5. The most effective solution for example (Wnuk and Karoń, 2014) with geometry changes of interchange

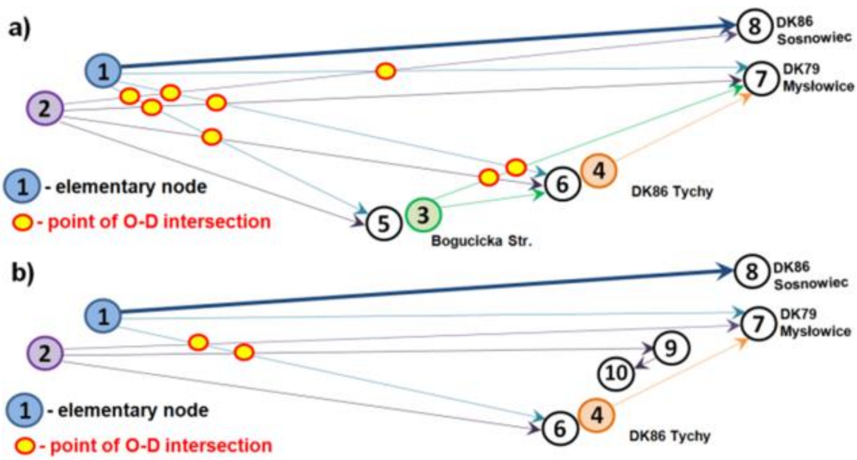


Fig. 6. Weaving diagrams: a) current weaving of traffic flows with eight points of origin-destination (O-D) intersections, b) most effective solution with only two points O-D intersections.

However, presented changes in traffic assignment may change traffic conditions in the next sections of transportation network – see Fig 4. with location of this place in the main big interchange in the urban ring roads (bypass). Therefore, intelligent transportation systems (ITS) with traffic management system and other ITS services are the best complex solution. The conception of ITS for Katowice city – capital of Upper-Silesian Agglomeration (Karoń and Mikulski, 2011a) has been presented in the Fig. 7. According to a study (Karoń and Mikulski, 2011a; Karoń and Sobota et al., 2014) the following main barriers to the implementation of ITS have been identified in Poland: insufficient knowledge of the potential beneficiaries and public users about functionalities offered by ITS systems and the different types of this systems, still small experience in the implementation of such projects in Poland (only 14 projects implemented in years 2007-2013 – from EU funds programme), and the lack of architecture of ITS deployment (all projects are "insular").

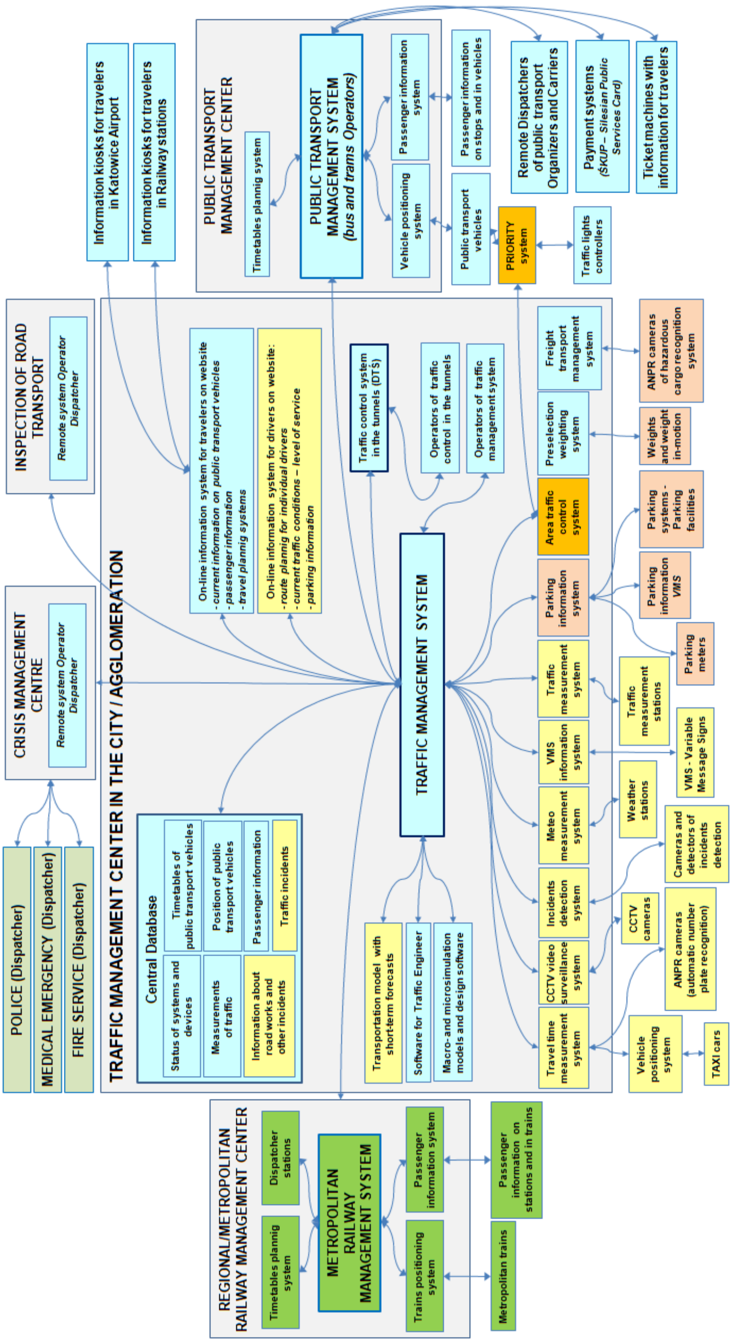


Fig. 7. Conception of ITS for Katowice City – capital of Upper-Silesian Agglomeration; based on (Karoń and Mikulski, 2011a; Mikołajczyk et al.).

The development of specific ITS solutions must take into account the diversity of their application needs arising from functional, spatial and organizational factors. On the one hand, local authorities and engineers are looking for the biggest functional scope of ITS, and on the other hand, they should take into account local needs of the cities, towns and urban agglomerations (Karoń and Mikulski, 2012). For example identification of needs differentiation of transportation investment has been the subject of research by questionnaire survey among 120 of 167 local municipality authorities in Silesia Region (Karoń and Sobota et al., 2014; Tomanek et al., 2013). There was indicated 23 predefined factors such as location of municipality in region, structure of the settlement, commercial building, science and education, health centers and health care, centers of culture, art, entertainment, sport and recreation, transportation infrastructure, structure of public transportation network, integration and priority for public transport, and many others. Based on results of this survey, for example, in Silesian Region there is variation and lack of consistency of spatial conditions for the functioning and development of public transport and implementation of ITS solutions (Karoń and Mikulski, 2012).In addition, ITS development processes may be dependent on the method of financing model with co-financing from the EU funds, e.g. increasing the use of territorial potentials through integrated interventions targeted at selected areas. This model is called the Integrated Territorial Investments (abbreviation in Polish: ZIT) and assumes: firstly, the common planning of strategic objectives and secondly the choice of activities and projects to fulfill the objectives consistent with strategic area of intervention. Such strategy has been prepared also for Central Subregion where Upper-Silesian Agglomeration is situated (Tomanek et al., 2013).

A good example of ITS development approach is the National Traffic Management System (abbreviation KSZR) of General Directorate for National Roads and Motorways (abbreviation GDDKiA). Basic benefits of KSZR are: minimization of the number and effects of traffic incidents by transferring warnings, redirecting traffic, more effective rescue operations, improved traffic flow, improved efficiency of road maintenance, better quality of freight transport handling (providing information on available parking spaces), provision of current and forecast information on traffic conditions regarding the national road system (INFOSTRATEGIA, 2012; Karoń and Mikulski, 2014).

## 5. Conclusions

Traffic congestion in the transportation network is characterized by minimum values of reserve capacities or lack of them (Żochowska, 2011). In addition, some reserves which could compensate for the effects of disruptions are "caught in the network" (e.g. due to the limited accessibility of the road, resulting from its technical class - the queue of vehicles “caught” on the freeway or expressway, passing through the agglomeration with a dense network of streets and urban roads). From the point of view of expected traffic smoothness, the analysis of traffic congestion in dense urban networks, requires both modelling of disruptions, their causes and how they impact on the elementary traffic flows in the transportation network nodes, and modelling the transportation network vulnerability to disruption (Żochowska, 2014c; Żochowska 2014d).

The assumptions about the smoothness of traffic flow, presented in this paper, may be supplemented by the postulated way of describing the traffic conditions in congested transportation networks (Woch, 1999; Woch, 2004). In such networks, with dense traffic flows and a high risk of the disruption (even in the form of a short queue of vehicles) the probability of suchanincident $p_i^j\left(\boldsymbol{Q}^j(sp)\right)$ seems to be a better measure of the probabilistic description of the capacity constraints than the expected waiting time $w_i^j\left(\boldsymbol{Q}^j(sp)\right)$ in the queue, because the probability takes into account the risk of delay in the traffic flow from the point of view of the person that plans a trip.

That is particularly important in congested networks, in which a high probability of queues is most often associated with high expected value of extension of travel time - as a result of the high risk of the large number of secondary disruptions and queues because of a sequence of following forms of congestion: the single interaction → the multiple interaction → bottleneck →triggerneck→ gridlock (Żochowska and Karoń, 2016).

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