CONGESTION INDICATORS FROM THE USERS' PERSPECTIVE: ALTERNATIVE FORMULATIONS WITH STOCHASTIC REFERENCE LEVEL

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ABSTRACT

Congestion causes delays and environmental impacts. Policy makers and transport planners have used congestion indicators for monitoring traffic conditions in urban areas. These indicators require defining a reference level of congestion (based for example on free flow conditions). In most cases reported in the literature this reference point is constant and typically corresponds to speed limits. This paper proposes a methodology for the definition of congestion indicators that takes into consideration the preferences and variability across individual commuters and hence, develops congestion indicators from the users of the system point of view. An analytical approach is developed pointing out that, as expected, for certain simple distributions of desired speed (i.e. triangular) some indicators are biased. A case study using a microscopic simulation model to study a small, dense, and very congested urban network in Stockholm illustrates the impact of applying this new definition in the calculation of congestion indicators. The results of the case study illustrate the bias of existing methods and identify indicators that are less sensitive to the distribution of the reference speed among drivers.

INTRODUCTION

Road traffic congestion produces undesirable impacts on urban centres. Delays and air pollution are examples of negative impacts widely considered. There is a lot of interest among decision makers and planners to monitor congestion, especially in urban areas. In this respect a number of congestion indicators have been developed and used for monitoring purposes. Lomax et. al. (Lomax, Turner et al. 1997) recognize that it is essential that congestion indicators are consistent with the goals and objectives in the metropolitan area they are used for and with the particular application.

Two main approaches for developing congestion indicators have been proposed in the literature: The *Bottleneck,* and the *Travel-time* (Morán and Bang 2006), with travel-time based indicators being more popular. Typically, congestion indicators for the travel time approach compare traffic conditions under congestion to some reference level. The reference level is usually based on the free–flow speed (TRB 2000), night time traffic levels (TfL 2003; Morán and Bang 2010), posted speed limits, etc. These approaches of defining the reference level however, ignore the fact that drivers, under free flow conditions, would travel at various speeds, reflecting their own preferences (desired speed). It is therefore of interest to evaluate the impact of using different reference levels for the calculation of congestion indicators.

The objective of this paper is to propose a methodology for taking into consideration, in the definition of the reference level for calculating congestion indicators, the preferences of the individual commuters and its variability and hence, develop congestion indicators from the users of the system point of view.

The paper is organized as follows. The next section reviews existing congestion indicators. The third section develops congestion indicators under various assumptions regarding the desired speed distribution across the population. The fourth section presents results from a case study that uses a microscopic simulation model to assess the significance of using desired speed (as opposed to free flow speed based on the speed limit) in the calculation of congestion indicators. The last section concludes the paper.

LITERATURE REVIEW

In this section we review congestion indicators that are based on the travel-time definition of congestion. A detailed inventory of congestion indicators and their evaluation can be found in (Morán 2008).

Excess Delay - ExD

This indicator was introduced by TfL in the context of the congestion charging system in London (TfL 2003). Congestion is defined as *the average excess or lost travel time experienced by vehicle users on a road network*. The corresponding indicator is defined as the *difference between the Observed Travel Rate* (TR_{obs}) *and the Reference Travel Rate* (TR_{ref}).

$$\mathrm{ExD} = \mathrm{TR_{obs}} - \mathrm{TR_{ref}}$$

Eq. 1

where,

$$\mathrm{TR_{obs}} = \frac{\sum_{i \in N} f_i \times tt_i}{\sum_{i \in N} f_i \times l_i}$$

Eq. 2

$$\mathrm{TR_{ref}} = \frac{\sum_{i \in N} f_i \times tt_i^{ref}}{\sum_{i \in N} f_i \times l_i}$$

Eq. 3

f_i is the flow on link *i*, tt_i is the travel time on link *i*, tt_i^{ref} is the travel time on link *i*, l_i is the length of link *i* and *N* is the number of links in the network.

The *Travel Rate* is the inverse of the *Network Speed* and describes the consumption of time per kilometer travelled in the network. The *Excess Delay*, defined in Eq. 1, is then the extra consumption per kilometer caused by congestion compared to the reference level. If information related to each individual driver *k* is available for each link, then the indicator becomes:

$$\mathrm{ExD} = \frac{\sum_{i \in N} \sum_{k \in I} tt_{i,k}}{\sum_{i \in N} \sum_{k \in I} l_{i,k}} - \frac{\sum_{i \in N} \sum_{k \in I} tt_{i,k}^{ref}}{\sum_{i \in N} \sum_{k \in I} l_{i,k}} [\mathrm{min/km}]$$

Eq. 4

where, $tt_{i,k}$ is the travel-time in link *i* for user *k* and $l_{i,k}$ is the length of the link *i* that is covered by user *k*. $tt_{i,k}^{ref}$ corresponds to the reference value for the travel-time for link *i* and user *k*.

Travel Time Index - TTI

The *Travel Time Index* has been used in various studies (Schrank and Lomax 2005). It is defined by the *ratio between the congested and non-congested or free-flow travel time*:

$$\mathrm{TTI} = \frac{\sum_{i \in N} \mathrm{VKT_i} \times \mathrm{TTI_i}}{\sum_{i \in N} \mathrm{VKT_i}} = \frac{\sum_{i \in N} \mathrm{VKT_i} \times \frac{tt_i}{tt_i^{ref}}}{\sum_{i \in N} \mathrm{VKT_i}}$$

Eq. 5

where, *VKT* is the vehicle-kilometers travelled in link *i*. The indicator can be expressed as:

$$\mathrm{TTI} = \frac{\sum_{i \in N} f_i \cdot l_i \times \frac{tt_i}{tt_i^{ref}}}{\sum_{i \in N} f_i \cdot l_i}$$

Eq. 6

where f_i is the flow in link i, and l_i is the length of link i. If information on individual trips is available the above becomes:

$$\mathrm{TTI} = \frac{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{l_{i,k}} \frac{\mathrm{tt_{i,k}}}{\mathrm{tt_{i,k}^{ref}}}}{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{l_{i,k}}}$$

Eq. 7

Relative Speed Reduction - RSR

Previous studies in Sweden (SRA 1999) used the *Relative Speed Reduction* as a congestion indicator for a link :

$$RSR_i = \frac{S_i^{ref} - S_i^{obs}}{S_i^{ref}} [\%]$$

Eq. 8

where S_i^{ref} is the reference speed and S_i^{obs} is the observed or measured speed in link i during the peak traffic period. The above link indicator can be aggregated to measure area congestion. Different approaches can be considered for aggregating this indicator. The ***W**eighted **A**verage Relative Speed Reduction* indicator is defined as:

$$\mathrm{RSR_{WA}} = \frac{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{l_{i,k}} \frac{S_{i,k}^{ref} - S_{i,k}}{S_{i,k}^{ref}}}{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{l_{i,k}}}$$

Eq. 9

Where $S_{i,k}^{ref}$ is the refence speed for user *k* in link *i* and $S_{i,k}$is the observed speed for road user *k* in link and $l_{i,k}$ is the distance covered in link *i* by user *k*.

Another expression for the *Relative Speed Reduction* indicator for an area network can be derived by considering the *Network Speed*, defined as the total distance travelled in the network divided by the total time spent in the network, as shown below in Eq. 10.

$$\begin{matrix}\text{Network}\\ \text{Speed}\end{matrix} = S_{NET} = \frac{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{l_{i,k}}}{\sum_{\mathrm{i\in N}} \sum_{\mathrm{k\in I}} \mathrm{tt_{i,k}}}$$

Eq. 10

The network level speed reduction indicator can the be derived by using the network speed in place of the **L**ink speed in Eq. 8.

$$\mathrm{RSR_L} = \frac{(\mathrm{S_{NET}})^{\mathrm{ref}} - (\mathrm{S_{NET}})^{\mathrm{OBS}}}{(\mathrm{S_{NET}})^{\mathrm{ref}}} = \frac{\frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}^{ref}}} - \frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}}}}{\frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}^{ref}}}}$$

Eq. 11

In empirical studies, the above indicator has shown to have the smallest confidence interval among other indicators (Morán 2008).

ANALYTICAL STUDY

The typical approach for the calculation of congestion indicators assumes that the reference value is based on the free flow speed, assumed constant across all drivers in the population. In this section we develop expressions for the travel-time-based congestion indicators reviewed in the previous section, assuming that under non-congested conditions the free flow speed has a distribution among the drivers (i.e. desired speed, used for example in the microscopic traffic simulation models).

The congestion indicators (CI) presented in the previous section can generally be considered as a function of observed or congested (x_{cong}) and reference parameters (x_{ref}) as shown in Eq. 12.

$$CI = f\left(x_{cong}, x_{ref}\right)$$

Eq. 12

Current methodologies consider as reference value the posted speed for all the users in the network. In this case the indicator can be expressed $CI_{POST} = f\left(x_{cong}, S_{POST}\right)$ where S_{POST} stands for the posted speed. Similarly, if the reference speed is given by the average free-flow speed across the population of drivers the indicator can be calculated by $CI_{MEAN} = f\left(x_{cong}, S_{MEAN}\right)$ where S_{MEAN} stands for the mean speed.

Calculation of Deterministic Indicators

From Eq. 7, a more useful expression can be obtained if it is assumed that all travelers in the network complete their trip at the end of the study period. Then, $l_{i,k}$ will be equal to l_i for all users. $n_{k(I)}$ is simply the number of vehicles in link *i*. Substituting $tt_{i,k}^{ref}$ by $l_i/S_{i,k}^{MEAN}$, the *Travel Time Index* becomes:

$$\mathrm{TTI_{MEAN}} = \frac{\sum_{\mathrm{i \in N}} \mathrm{l_i} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}} \frac{S_i^{MEAN}}{l_i}}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} = \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} S_i^{MEAN} \cdot \overline{\mathrm{tt}}_{\mathrm{i}} \cdot n_{k(I)}$$

Eq. 13

where, $\overline{tt}_i$ is the congested travel time in link *i* and S_i^{MEAN} is the mean speed.

If the posted speed is used is used instead of the mean speed then:

$$\mathrm{TTI}_{\mathrm{POST}} = \frac{1}{\sum_{\mathrm{i}\in\mathrm{N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i}\in\mathrm{N}} S_i^{POST} \cdot \overline{\mathrm{tt}}_{\mathrm{i}} \cdot n_{k(I)}$$

Eq. 14

From Eq. 4 and using a similar assumption, the *Excess Delay* becomes:

$$\begin{aligned}\mathrm{ExD}_{\mathrm{MEAN}} &= \frac{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \mathrm{tt_{i,k}}}{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \mathrm{l_{i,k}}} - \frac{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \mathrm{tt_{i,k}^{ref}}}{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \mathrm{l_{i,k}}} = \mathrm{TR_{OBS}} - \frac{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \frac{l_i}{S_i^{MEAN}}}{\sum_{\mathrm{i}\in\mathrm{N}} \sum_{\mathrm{k}\in\mathrm{I}} \mathrm{l_{i,k}}} \\ &= \mathrm{TR_{OBS}} - \frac{1}{\sum_{\mathrm{i}\in\mathrm{N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i}\in\mathrm{N}} \frac{1}{S_i^{MEAN}} \cdot \mathrm{l_i} \cdot n_{k(I)}\end{aligned}$$

Eq. 15

If the posted speed is used is used instead of the mean speed then:

$$\mathrm{ExD}_{\mathrm{POST}} = \mathrm{TR_{OBS}} - \frac{1}{\sum_{\mathrm{i}\in\mathrm{N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i}\in\mathrm{N}} \frac{1}{S_i^{POST}} \cdot \mathrm{l_i} \cdot n_{k(I)}$$

Eq. 16

Calculation of Stochastic Indicators

Assuming that the desired speed has a known distribution among the users of the system, the indicator can be calculated as $CI_{STOCH} = f\left(x_{cong}, S_{STOCH}\right)$. We will illustrate the calculation of the indicators assuming that the desired speed has a triangular distribution. Figure 1 below shows an example of a generic Triangular distribution. The y-axle corresponds to the *probability density function* (pdf) and the x-axle corresponds to the speed. It can be observed that the parameters for this distribution are S_a, S_b and S_c where S_a is the minimum value, S_b is the maximum and S_c is the mode.

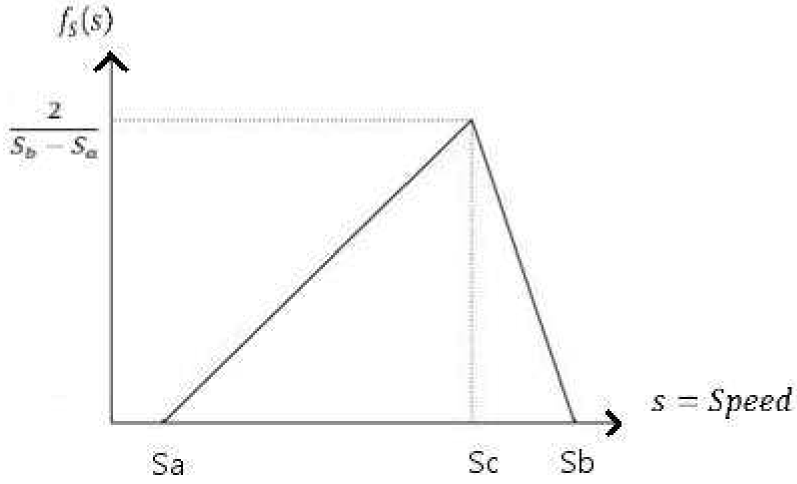

Figure 1 - Triangular distribution

The *probability density function* (pdf) is defined by:

$$f_S(s|\mathrm{S_a}, \mathrm{S_b}, \mathrm{S_c}) = \begin{cases} \dfrac{2(s - \mathrm{S_a})}{(\mathrm{S_b} - \mathrm{S_a})(\mathrm{S_c} - \mathrm{S_a})}; \mathrm{S_a} < s < S_c \\ \dfrac{2(\mathrm{S_b} - s)}{(\mathrm{S_b} - \mathrm{S_a})(\mathrm{S_b} - \mathrm{S_c})}; \mathrm{S_c} < s < S_b \end{cases}$$

Eq. 17

With a *Cumulative Distribution Function* (CDF) given by:

$$\mathrm{F_S}(s|\mathrm{S_a}, \mathrm{S_b}, \mathrm{S_c}) = \begin{cases} \dfrac{(s - \mathrm{S_a})^2}{(\mathrm{S_b} - \mathrm{S_a})(\mathrm{S_c} - \mathrm{S_a})}; \mathrm{S_a} < s < S_c \\ \dfrac{2(\mathrm{S_b} - s)^2}{(\mathrm{S_b} - \mathrm{S_a})(\mathrm{S_b} - \mathrm{S_c})}; \mathrm{S_c} < s < S_b \end{cases}$$

Eq. 18

The expected value is given by:

$$E[s] = \frac{S_a + S_b + S_c}{3}$$

Eq. 19

The parameters of the distribution will vary depending on a large list of factors (time of the day, personal preferences, type of infrastructure) and will not be covered in the present study. The present study will focus on estimating the impacts of neglecting this distribution in the estimations. Assuming a triangular distribution for the desired speeds, the travel time index can be estimated as:

$$\mathrm{TTI_{STOCH}} = \mathrm{E[TTI]} = \int_0^{\infty} \mathrm{TTI}\left(\mathrm{obs}, \mathrm{S^{ref}}\right) \mathrm{f_S}\left(\mathrm{s^{ref}}\right) \mathrm{ds} = \int_0^{\infty} \frac{\sum_{\mathrm{i \in N}} \mathrm{l_i} \sum_{\mathrm{k \in I}} \frac{\mathrm{tt_{i,k}}}{\mathrm{tt_{i,k}^{ref}}(\mathrm{s^{ref}})}}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} f_S(s) \mathrm{ds}$$

Then,

$$\mathrm{TTI_{STOCH}} = \int_0^{\infty} \frac{\sum_{\mathrm{i \in N}} \mathrm{l_i} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}} \frac{s_{i,k}^{ref}}{l_i}}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \mathrm{f_S(s)ds} = \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}} \cdot \mathrm{E}\left[s_i^{ref}\right]$$
$$= \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} \mathrm{E}\left[s_i^{ref}\right] \cdot \overline{\mathrm{tt}}_{\mathrm{i}} \cdot n_{k(I)}$$

Eq. 20

Comparing Eq. 13, Eq. 14, and Eq. 20, it is observed that the estimators, as expected, have the same value if $\mathrm{E}\left[\mathrm{s_i^{ref}}\right] = S_i^{POST} = S_i^{MEAN}$.

The Excess Delay indicator, assuming the same distribution of the desired speed, can be derived as follows:

$$\mathrm{ExD_{STOCH}} = \int_0^{\infty} \mathrm{ExD}\left(\mathrm{obs}, \mathrm{s^{ref}}\right) \mathrm{f_S}\left(\mathrm{s^{ref}}\right) \mathrm{ds} = \int_0^{\infty} \left(\frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}} - \frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}^{ref}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}} \right) \mathrm{f_S(s)ds}$$
$$= \left(\frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}}}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}} \right) \int_0^{\infty} \mathrm{f_S(s)ds} - \int_0^{\infty} \left(\frac{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{tt_{i,k}^{ref}}\left(\mathrm{s^{ref}}\right)}{\sum_{\mathrm{i \in N}} \sum_{\mathrm{k \in I}} \mathrm{l_{i,k}}} \right) \mathrm{f_S(s)ds}$$

Given that $\int_0^{\infty} \mathrm{f_S}(s)\mathrm{ds} = 1$ and $t_{i,k}^{ref} = \frac{l_i}{s_{i,k}^{ref}}$, then $\mathrm{ExD_{STOCH}}$ becomes:

$$\mathrm{ExD_{STOCH}} = \mathrm{TR_{obs}} - \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} \mathrm{l_i} \sum_{\mathrm{k \in I}} \int_0^{\infty} \frac{1}{\mathrm{s^{ref}}} \mathrm{f_S(s)ds}$$
$$= \mathrm{TR_{obs}} - \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} \mathrm{l_i} \sum_{\mathrm{k \in I}} \mathrm{E}\left[\frac{1}{\mathrm{s^{ref}}}\right] =$$
$$= \mathrm{TR_{obs}} - \frac{1}{\sum_{\mathrm{i \in N}} \mathrm{l_i} \cdot n_{k(I)}} \sum_{\mathrm{i \in N}} \mathrm{E}\left[\frac{1}{\mathrm{s^{ref}}}\right] \cdot \mathrm{l_i} \cdot n_{k(I)}$$

Eq. 21

$E\left[\frac{1}{s^{ref}}\right]$ is calculated using that $S^{ref} \in Triang(S_a, S_c, S_b)$. With some arithmetical work it is obtained that:

$$E\left[\frac{1}{s^{ref}}\right] = 2\left(\frac{\mathrm{S_b \ln S_b - S_b \ln S_c + S_c - S_b}}{\mathrm{(S_b - S_a)(S_b - S_c)}} + \frac{\mathrm{S_c - S_a + S_a \cdot \ln S_a - S_a \cdot \ln S_c}}{\mathrm{(S_b - S_a)(S_c - S_a)}} \right)$$

Eq. 22

Comparing Eq. 15 and Eq. 21 it can be observed that the estimator would have the same value if — ——. But ——— and this indicates that some indicators are inherently biased due to the non-linear relationship of the expected values.

CASE STUDY

In order to verify the intuition gained in the previous section and estimate the effects in a practical application, a case study was conducted using the microscopic simulation model VISSIM with a small network. The microscopic simulation environment allows the collection of all needed data to calculate the congestion indicators.

A previously calibrated and validated network of a central area in Stockholm is used (Kovaniemi and Lukonin 2008). The simulated network is shown in Figure 2. The network includes a highly congested arterial (Valhallavägen between Lidingövägen and Roslagstull). Valhallavägen carries the highest flows among urban streets in Stockholm. Since Valhallavägen also connects Stockholm to the port (Frihamn) a significant number of trucks and heavy vehicles also uses the network. The flow in the lateral streets is not significant except for Lidingövägen, Odengatan and Engelbreksgatan. "Tekn. hög-skolan" is the location of a commuter train station and a bus terminal serving the north part of the Stockholm region. Hence, there is also significant bus traffic in the network.

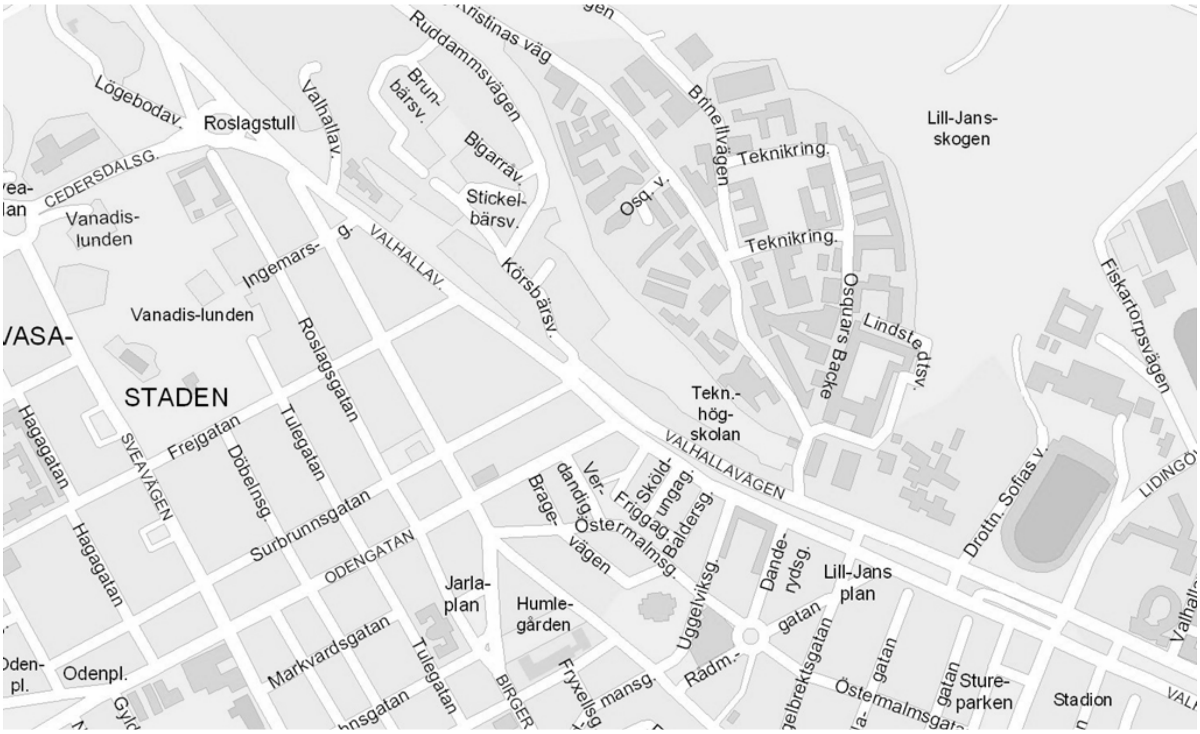

Figure 2: *Area of study: Vallhallavägen (Kovaniemi and Lukonin 2008)*

Experimental Design

The posted speed in the area is considered to be 50km/h for all links. Two scenarios were considered with respect to the desired speed. In the FAST scenario the distribution is biased towards speeds higher than the speed limit (i.e the mean desired speed is larger than posted speed). In the SLOW scenario, speeds are biased towards speeds lower than the speed limit (i.e mean desired speed is smaller than posted speed). Table 1 summarizes the characteristics of each scenario. For each scenario 25 replications of 1 hour of operations were conducted.

Table 1 *- Desired Speed Distributions for each vehicle type*

Experiment denomination	Vehicle Type	Parameters				
		Posted	Sa	Sc	Sb	Mean
FAST	Cars	50	40	59	60	53
	Trucks	50	40	53	60	51
	Buses	50	40	56	60	52
SLOW	Cars	50	40	47	60	49
	Trucks	50	40	41	60	47
	Buses	50	40	44	60	48

Results

Figure 3 shows the percentage error in the estimation of the *Excess Delay (ExD)* when using the MEAN or POST speed instead of the underlying distribution of desired speeds, i.e. STOCH.

$$CI\ Error_{POST}\ [\%] = \frac{CI_{POST} - CI_{STOCH}}{CI_{STOCH}}$$

Eq. 23

$$CI\ Error_{MEAN}\ [\%] = \frac{CI_{MEAN} - CI_{STOCH}}{CI_{STOCH}}$$

Eq. 24

The errors tend to be larger for lower levels of congestion and they asymptotically decrease as congestion increases. The results show that the calculation based on the mean speed has smaller error (absolute value) than the one based on the posted speed.

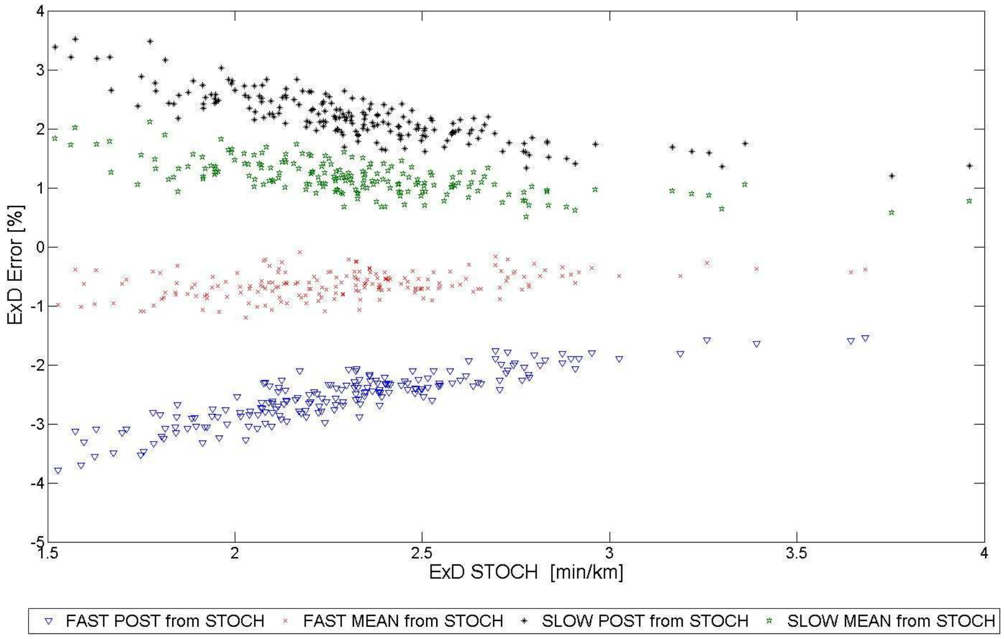

Figure 3 – Excess Delay – Estimation Error

Figure 4 illustrates the results for the congestion indicator based on the *Travel Time Index (TTI)*. In this case the percentage error remains constant through the whole range of congestion levels.

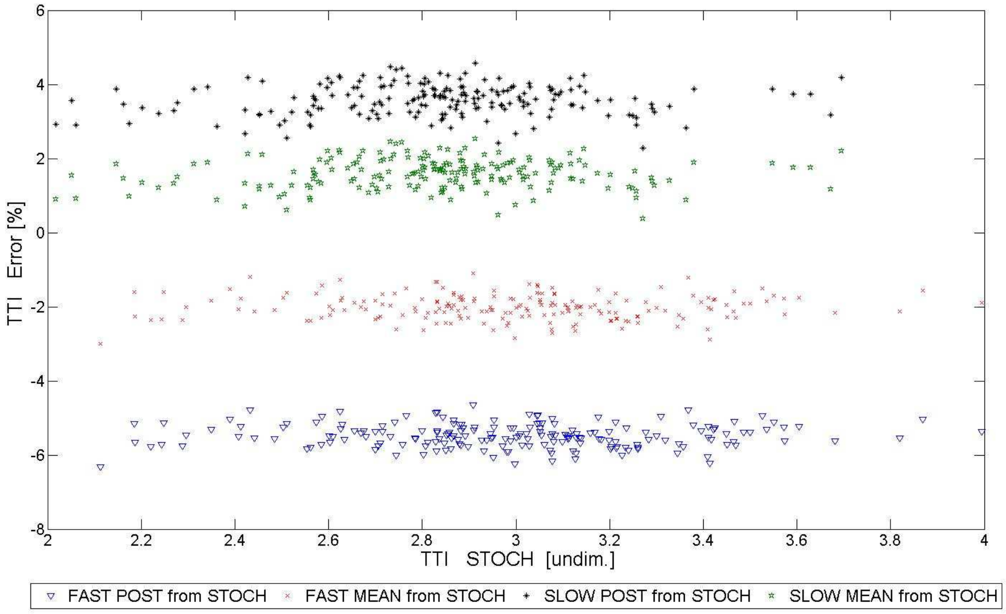

Figure 4 - Travel Time Index - Estimation Error

Figure 5 and Figure 6 summarizes the results for the *Relative Speed Reduction* indicator illustrating the relative error. Both aggregation methods, $\mathrm{RSR_{WA}}$ & $\mathrm{RSR_{L}}$, have an error that decreases as the congestion levels increases. It is also observed that errors for $\mathrm{RSR_{L}}$ are smaller than errors for $\mathrm{RSR_{WA}}$.

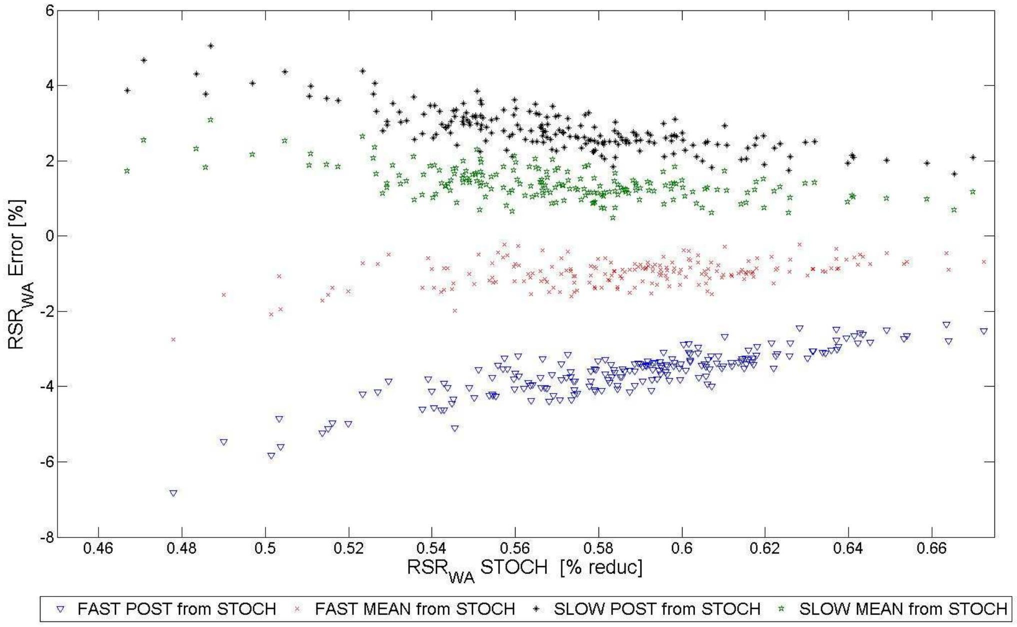

Figure 5 – Relative Speed Reduction – RSR_{WA} - Estimation Error

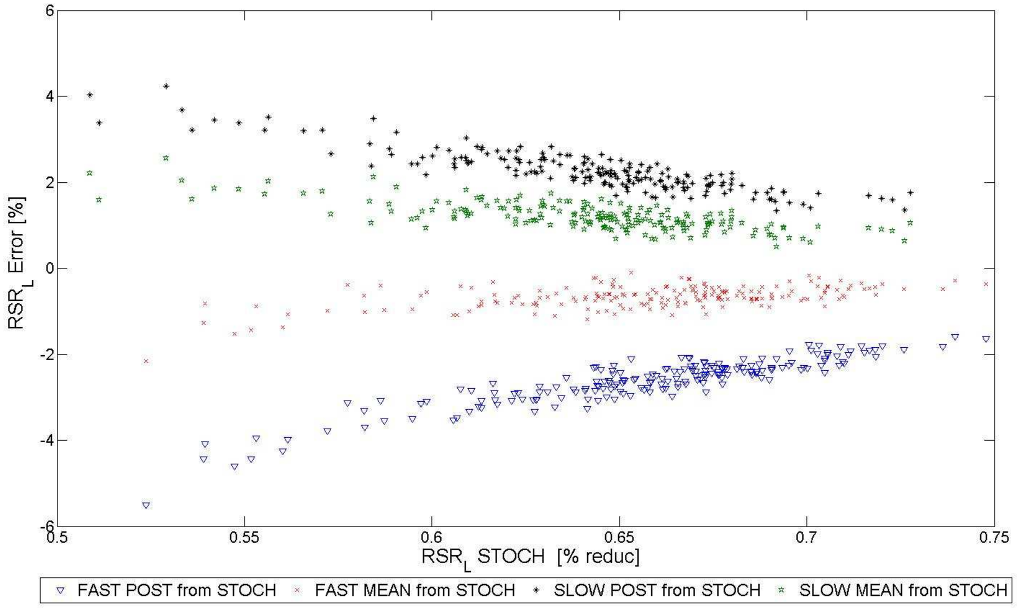

Figure 6 – Relative Speed Reduction – RSR_{L} - Estimation Error

In summary, the error in calculating the various travel-time-based congestion indicators is smaller, in absolute value, in the SLOW scenario (negative bias) than in the FAST scenario (positive bias). The error is decreasing with the congestion levels from 6% to 1%. The estimation of the TTI showed constant error values across congestion levels.

CONCLUSION

Measuring congestion in urban road areas using appropriate congestion indicators is becoming increasingly important. Current indicators based on the travel-time definition of congestion were reviewed. These indicators use a reference speed that corresponds to the free flow speed on the links in the network. Therefore, they ignore the desired speed distribution among the drivers. This paper extends the definition of the indicators to incorporate desired speed distribution and hence, calculate congestion indicators more accurately. In addition, the modified indicators are more likely to measure congestion from the user's point of view.

The paper developed analytical expressions for the calculation of various congestion indicators. As expected, the analysis shows that some indicators, as calculated in previous studies, are biased and tend to overestimate or underestimate congestion, depending on the desired speed distribution.

A case study, using microsimulation, with a small congested network was used to illustrate the impact of using a more appropriate definition for congestion indicators. Three approaches for calculating each indicator were considered by using different reference speeds:

- the speed limit or posted speed (POST),
- the mean value of the desired speed distribution (MEAN), and
- the actual desired speed distribution (STOCH).

The results show that the errors ranged from *1% to 4%* depending on congestion levels and that the error was larger when using the posted speed than the mean desired speed. It is observed also that some indicators presents an constant error across different level of congestion (i.e. TTI) meanwhile others present decreasing errors with congestion.

As the distribution of desired speed becomes available (i.e. the empirically obtained parameters of the distribution) the presented congested indicators will be able to summarize the impacts of congestion for the study area, considering at the same time the variability of the reference value across the population.

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