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Congestion Indicators and Congestion Impacts: A Study on the Relevance of Area-wide Indicators

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Abstract

Congestion indicators for monitoring congestion in road area networks have been devised to use the output of long-term planning models which makes them insensitive to the dynamics of congestion or pollutant emissions. The objective of the present study is to compare the capabilities of different congestion indicators for describing congestion impacts (delays and emissions) considering a dynamic framework analysis. Microsimulation is used for estimating the congestion indicators as well as the congestion impacts in a disaggregated and dynamic mode. The indicators with the best descriptive capabilities are identified. Recommendations about indicators are provided for road practitioners.
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Keywords: Pollutant emissions; Traffic performance measures; Traffic simulation;

1. Introduction

Road traffic congestion produces undesirable impacts on urban city centres. Delays and air pollution are well-known negative examples of these impacts and several policies have endeavored to reduce them. Politicians, decision makers and traffic planners have strived to estimate the sustainability and efficiency of the mitigation policies applied at an area-wide level using congestion indicators. These congestion indicators are used as proxies for the real impact due to the elevated cost of estimating the actual impacts through recurrent and periodical monitoring efforts. Thus, the chosen indicator is expected to be a good descriptor of the congestion impacts, i.e. delay, emissions, etc (Litman 2007).

Two main shortcomings can be indentified for these indicators. First, these indicators were originally created to use the output of long-term planning and evaluation models. Therefore, these indicators are not sensitive to the dynamic and time dependent aspects of congestion (Merritt and Bång 2000). In this same path, despite the improvements and advances in recent years in the field of data collection methods and microsimulation the indicators are still using data aggregated at the same level as the long-term planning tools. Second, the indicators were devised to measure the impact in travel time (i.e. delay). HCM provides methodologies for the dimensioning and evaluation of *traffic performance* of different types of installations (i.e. uninterrupted flow, interrupted flow

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arterials, prioritized intersections, etc)(TRB 2000). Recent awareness of other traffic impacts (i.e. emissions) provides a new dimension in which the congestion indicators need to be evaluated. Several efforts have recently been carried out for different levels of aggregation (i.e. link, intersections, metropolitan areas, etc) (Bigazzi and Bertini 2009; Choi and Frey 2010). However, for monitoring congestion impacts in different types of traffic installations, the capability of the area-wide indicators has not been studied in terms of the available enhanced data capabilities or the environmental aspects.

1.1. Objective

The objective of the present study is to compare the capabilities of congestion indicators to describe the impacts of traffic congestion on an area-wide level. For this purpose it is required to further develop the existing congestion indicators in order to make them suitable for a dynamic analysis.

1.2. Scope and limitations

Transportation research has used congestion indicators in several other ways. For example, they can be used as policy design variables (i.e. estimating the optimum toll on a certain road), for monitoring traffic conditions (i.e. estimating the impact of a certain applied policy), etc. The current study considers area-wide indicators for monitoring purposes, that is, for empirical estimations of the congestion levels for evaluation of different policies (i.e. parking in central zones, car free zones, large scale transit investment, congestion charging, etc).

Also, congestion indicators need to be i) statistically confident, ii) a useful tool to communicate with the intended audience and iii) relevant with respect to the impacts caused by congestion (SRA 1999). The present study focuses on this last aspect of the indicators. Besides “delays”, the emissions to be considered are Carbon Monoxide emissions (CO1), Carbon Dioxide emissions (CO2), Hydrocarbon emissions (HC), Nitrogen Oxide emissions (NOx) as well as fuel consumption.

Methods for measuring emissions at an area level are usually affected by the ruling weather conditions at the moment when the data collection takes place. On the other hand, if every single vehicle is measured, the elevated cost would make the analysis prohibitive. Microsimulation has been preferred in recent studies due to the possibilities of obtaining data in an extremely disaggregated manner (Chen and Yu 2007; Zhang et al. 2009) and recent efforts have focused on implementing an integrated approach (Stevanovic et al. 2009). A detailed description and review of the literature about simulation and emissions can be found in (Smit et al. 2008). Thus, microsimulation is used because it allows data to be collected in an extremely disaggregated manner in time and space dimensions.

In a simulation environment, where the impacts (delay for example) are perfectly known, the congestion indicators lose their importance. In practical applications, the impacts are not known and the indicators are used as proxies. The present study uses data where *impacts* and the *impact proxies* (i.e. congestion indicators) are known in order to compare their descriptive capabilities.

The structure of the paper is as follows: the first section is the present introduction. The second section presents definitions of congestion and some issues related to area-wide congestion indicators. The third section presents the methodology for estimating the impacts and describes the experiment. The fourth presents the results and analysis. The fifth section presents the conclusions of the study. The discussion is presented in the last section.

2. Definition of congestion & congestion indicators

The first subsection discusses the approaches of defining congestion existing in the literature. The later subsection presents a selection of indicators in the literature and further develops them to make them suitable to a study sensitive to the dynamics of congestion.

2.1. Definitions of congestion

The literature presents two approaches for defining congestion: The travel-time approach and the bottleneck approach (Morán and Bang 2006).

The *travel-time* approach considers indicators that contrast the observed or congested traffic conditions (using travel time or journey speed) with some reference level. Two shortcomings can be identified with this approach: first, trips need to be ended for estimating the impact of congestion, increasing the latency of the estimations. Second, there is no agreement in the estimation of the reference level and its estimation using empirical non-congested data can present great inconsistencies (Morán and Bång 2010). Regarding the indicators related to this definition, the poor detail in the time aggregation has affected space aggregation. Space aggregation issues have been solved using weighted averages. The considered weights have been traffic parameters at link level (for example flow, flow x length or length of the selected links (Bremmer et al. 2004; City of Stockholm 2006; Lomax et al. 1997; SRA 1999)). A detailed inventory of congestion indicators and their evaluation can be found in (Morán 2008).

The *bottleneck* approach relates to demand exceeding capacity in a punctual location (TRB 2000). However, demand cannot be empirically observed when it exceeds capacity. Thus, an observable symptom is the created queue or dense flow. A shortcoming with this definition is the definition of the queuing threshold because it depends on the traffic facility under analysis (i.e. highways might show moving jams while intersections show totally stopped vehicles). Also, the estimation of queues presents data collection difficulties and no agreement has been achieved regarding the aggregation methodology (Morán and Bång 2010). Empirical studies have used the two-fluid model for estimating area-wide parameters (Herman and Prigogine 1979). These efforts have used empirical data and have provided high explanatory value (Amini et al. 1998). However, the assumptions of the two fluid modeling and the required data collection restrict its applicability. There is no monitoring system currently using this modeling approach.

The comparison of indicators from the *bottleneck* and *travel-time* approach using empirical data has been done but only applied to a single road segment (Bang 2006). For area-wide analysis, no analysis has been carried out comparing both approaches, neither empirically nor using microsimulation.

Important advances have recently been achieved on the phenomena modeling front at an area-wide level (Daganzo and Geroliminis 2008). They provide a detailed description of the relationships between traffic parameters like flow, speed, and occupancy at an area level, but they do not explicitly consider a congestion indicator.

2.2. Inventory of the congestion indicators

Five congestion indicators are considered in the present study: four of them relate to the travel-time approach of defining congestion and one relates to the bottleneck approach.

2.2.1. Excess Delay - ExD

Excess Delay (ExD) 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}).

$$\mathrm{ExD} = \mathrm{TR_{obs}} - \mathrm{TR_{ref}} = \frac{\sum_{i\in N} f_i \times tt_i}{\sum_{i\in N} f_i \times l_i} - \frac{\sum_{i\in N} f_i \times tt_i^{ref}}{\sum_{i\in N} f_i \times l_i} \tag{1}$$

where, f_i is the flow on link i, tt_i is the travel time on link i, tt_i^{ref} is the reference 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 from each individual driver k is available for each link, then the indicator becomes:

$$\mathrm{ExD} = \frac{\sum_{i\in N}\sum_{k\in I} tt_{i,k}}{\sum_{i\in N}\sum_{k\in I} l_{i,k}} - \frac{\sum_{i\in N}\sum_{k\in I} tt_{i,k}^{ref}}{\sum_{i\in N}\sum_{k\in I} l_{i,k}} \tag{2}$$

2.2.2. Travel Time Index - TTI

The Travel Time Index (TTI) has been used in various studies mainly in United States (Schrank and Lomax 2005). It is defined as the ratio between the congested and non-congested or free-flow travel times. As VKT_i is the Vehicle-Kilometers Travelled in link i, the indicator can be expressed as:

$$\mathrm{TTI} = \frac{\sum_{i\in N} \mathrm{VKT}_i \times \mathrm{TTI}_i}{\sum_{i\in N} \mathrm{VKT}_i} = \frac{\sum_{i\in N} \mathrm{VKT}_i \times \frac{tt_i}{tt_i^{ref}}}{\sum_{i\in N} \mathrm{VKT}_i} = \frac{\sum_{i\in N} f_i \cdot l_i \times \frac{tt_i}{tt_i^{ref}}}{\sum_{i\in N} f_i \cdot l_i} \tag{3}$$

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 expression above becomes:

$$\mathrm{TTI} = \frac{\sum_{i\in N}\sum_{k\in I} l_{i,k} \frac{tt_{i,k}}{tt_{i,k}^{ref}}}{\sum_{i\in N}\sum_{k\in I} l_{i,k}} \tag{4}$$

2.2.3. Relative Speed Reduction - RSR

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

$$\mathrm{RSR}_i = \frac{S_i^{ref} - S_i^{obs}}{S_i^{ref}} [\%] \tag{5}$$

where S_i^{ref} is the reference speed and S_i^{obs} is the observed or measured speed on 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 Weighted Average Relative Speed Reduction (RSR_{WA}) indicator is defined as:

$$\mathrm{RSR}_{WA} = \frac{\sum_{i\in N}\sum_{k\in I} l_{i,k} \frac{S_{i,k}^{ref} - S_{i,k}}{S_{i,k}^{ref}}}{\sum_{i\in N}\sum_{k\in I} l_{i,k}} \tag{6}$$

where $S_{i,k}^{ref}$ is the reference speed for user k on link i, $S_{i,k}$ is the observed speed for road user k on link i, and $l_{i,k}$ is the distance covered on 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. 7).

$$\begin{matrix}\text{Network}\\ \text{Speed}\end{matrix} = S_{NET} = \frac{\sum_{i\in N}\sum_{k\in I} l_{i,k}}{\sum_{i\in N}\sum_{k\in I} tt_{i,k}} \tag{7}$$

The network level speed reduction indicator can be derived by using the network speed, S_{NET}, instead of the Link speed, S_i, in Eq. 5.

$$\mathrm{RSR}_L = \frac{(S_{NET})^{ref} - (S_{NET})^{OBS}}{(S_{NET})^{ref}} = \frac{\frac{\sum_{i\in N}\sum_{k\in I} l_{i,k}}{\sum_{i\in N}\sum_{k\in I} tt_{i,k}^{ref}} - \frac{\sum_{i\in N}\sum_{k\in I} l_{i,k}}{\sum_{i\in N}\sum_{k\in I} tt_{i,k}}}{\frac{\sum_{i\in N}\sum_{k\in I} l_{i,k}}{\sum_{i\in N}\sum_{k\in I} tt_{i,k}^{ref}}} \tag{8}$$

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

2.2.4. Queue indicator

The bottleneck approach considers, in general, design variables or apriori parameters (i.e. travel demand). Unfortunately, demand cannot be empirically observed when its value is above capacity. In this way, queue becomes suitable for empirical estimations using this approach. "Time in queue" is the usual indicator when dealing with links or single servers (for example using the Markov MM1 model). However, in road networks where vehicles circulate at speeds that vary in a continuous range, "Standing-Still-Seconds" (SSS) will be a more adequate indicator.

The literature shows some studies aggregating indicators for road network areas using the critical speed for queuing as under 3 km/h with no consideration of the distance to the previous car (Amini et al. 1998). This is a sound assumption when considering streets in the city centre and it will be used this study.

3. Methodology

The first and second subsection describes the methodology estimation for the congestion impacts. The third subsection describes the areas considered for the analysis and the simulation platforms used in the study.

3.1. Congestion impacts on traffic performance

The present study estimates the impacts in narrow time slices (1 second) and later aggregated in time intervals (5 minutes). The estimation of the delay considers constant speed v_t during the time slice t=1. Then, the vehicle k covers a $distance_{k,t}= tt_t*v_{k,t}$. If the car would have travelled at the non-congested speed (i.e. $v_{k,t}^{ref}$), it would have travelled the same $distance_{k,t}$ in a time $tt_{k,t}^{ref}=distance_{k,t}/v_{k,t}^{ref} = tt_t*v_{k,t}/v_{k,t}^{ref}$. The delay during time slice t for vehicle k will be the difference between tt_t and $tt_{k,t}^{ref}$ as shown in Eq. 9.

$$\mathrm{Delay}_{k,t} = \mathrm{tt}_t\left(1-\frac{v_{k,t}}{v_{k,t}^{ref}}\right) = \left(1-\frac{v_{k,t}}{v_{k,t}^{ref}}\right) \tag{9}$$

The delay for time interval T will be the sum over the time slices t and the vehicles k as shown in Eq. 10

$$Delay_T = \sum_k \sum_{t=t_T^{start}}^{t_T^{end}} \left(1-\frac{v_{k,t}}{v_{k,t}^{ref}}\right) \tag{10}$$

3.2. Congestion impacts on pollutant emissions

Instantaneous emissions were used in the present study, given the dissagregated level of the vehicle information. The emissions (CO, CO2, HC, NOx, and PM) and fuel consumption in the current study are estimated using the MODEM model. This model estimates pollutants for each second based mainly on instantaneous speed and acceleration (Joumard, Jostb et al. 1992). The values are later aggregated for the same time interval as delay. The MODEM project was initially created by a consortium during the Drive V1053 EU Project MODEM, and is now managed by TRL-UK (Joumard, Hickman et al. 1992).

3.3. Areas of study and simulation platforms

The characteristics of the selected zones are: interrupted flow, mixture between residential and commercial areas, reduced parking and two or more road hierarchy types of the road network. Previously calibrated and validated networks of central areas of Stockholm are used (Kovaniemi and Lukonin 2008; Morán and Koutsopoulos 2010). The first area is shown in FIGURE 1. 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 use the network. The flow in the lateral streets is not significant except on Lidingövägen, Odengatan and Engelbreksgatan. "Tekn.-hög-skolan" is the location of a commuter train and subway station and a bus terminal serving the northern part of the Stockholm region. Hence, there is also significant bus traffic in the network.

The second area corresponds to the Sankt Eriksplan area in the North-centre of Stockholm (Norrmalm) as show in FIGURE 2. This network includes two arterials (Torsgatan & Sankt Eriksgatan). These arterials connect the northern part of the city with the city centre and the West-centre of Stockholm. There are two frequent lines of public transport operating in the area and there are also marked bicycle lanes with a significant flow. Parking is prohibited on most of the main streets, but some parking places are located on minor streets (for example Sigtunagatan, Gästrikgatan, Birkagatan).

The simulations were carried out in VISSIM (PTV 2009). This simulation software can apply different random seeds for generating the flow in the inputs. 20 random seeds were considered for each of the zones. The first time three intervals (i.e. the first 15 minutes) are part of the warming up of the network and then excluded from the analysis. The number of observations per site becomes 20x(15-3)=240. The simulation considered peak AM traffic flows and considered only road transport modes. Buses are generated based on timetables while trucks are a percentage of the total flow. Bicycles and motor vehicles do not share the same links, but the interaction between these modes occurs at the intersections when, for example, turning motor vehicles have to give way to bicycles driving straightforward. Further descriptions of the calibration and validation can be found in (Kovaniemi and Lukonin 2008; Morán and Koutsopoulos 2010).

FIGURE 1: Area of study: Vallhallavägen

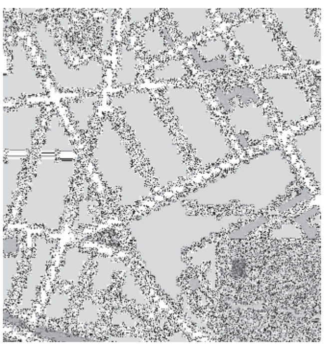

FIGURE 2: Area of study: Sankt Eriksplan

4. Results & analysis

The first subsection presents the results of the simulation study and correlation estimation (specifically using the R2-values). The second subsection contrasts the obtained results with previous experiences.

The impacts of congestion are expressed in total area-wide values divided by the vehicle-kilometers travelled during the interval of analysis. Dividing the total impacts by the vehicle-kilometers provides a better comparison between the two areas of different sizes. The impacts are:

- Delay [seconds/veh-km]
- Carbon Monoxide emissions CO [mg/veh-km]
- Hydrocarbon emissions HC [mg/veh-km]
- Carbon Dioxide emissions CO2 [mg/veh-km]
- Fuel consumption [mg/veh-km]
- Nitrogen Oxide emissions NOx [mg/veh-km]

The congestion indicators to be considered are:

- "Excess Delay;" ExD [min/km]
- "Travel Time Index;" TTI [%]
- "Relative Speed Reduction – Weighted Average;" RSR_WA [%]
- "Relative Speed Reduction – networks as a Link;" RSR_L [%]
- “Standing Still Seconds”; SSS [seconds]

4.1. Impact versus congestion indicator correlation analysis

Scatter plots can be generated for each pair impact-indicator (congestion impact on the y-axis and a congestion indicator on the x-axis). FIGURE 3 shows examples of the scatter plots having on the vertical axis Delay impact (first row in graphs a, b, c, and e) and CO1 emissions (second row in graphs f, g, h, i, and j).

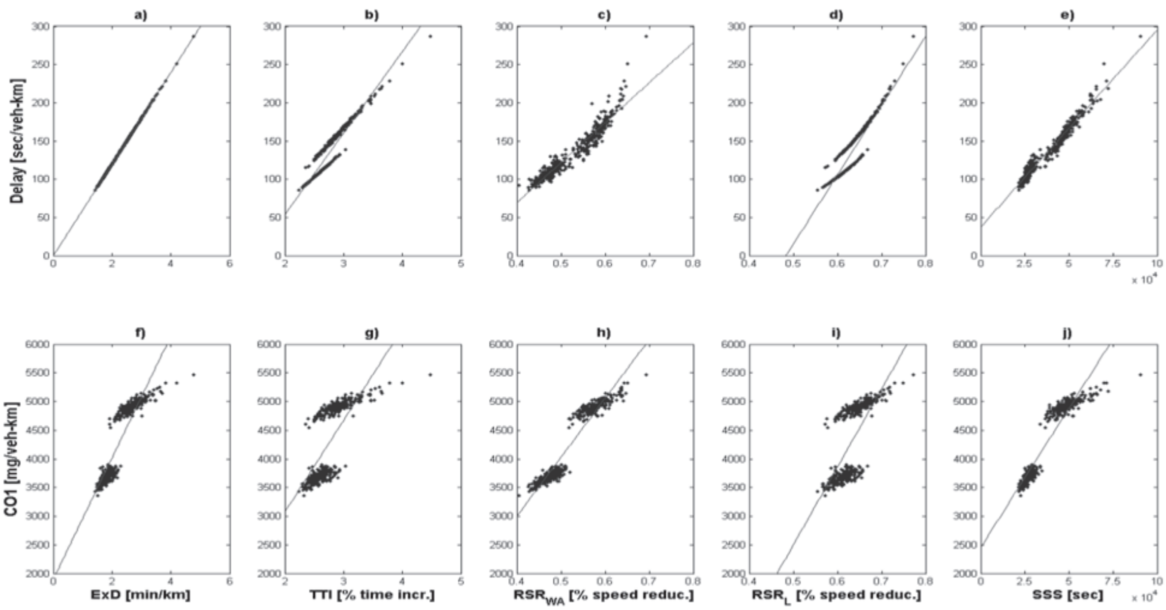

FIGURE 3: Scatter plots: Delay and CO1 vs. Congestion Indicators (ExD, TTI, RSRWA, RSRL, SSS)

For the case of delay and given the formulation of the indicator, the fit is almost perfect, obtaining a slope of 60 and an intercept of -5.5e-014. The intercept is not significantly different from zero and the slope value is due to unit transformation (seconds to minutes). It can be observed that the indicators based on the journey speed, RSR_{WA} and RSR_L (i.e. c and d) show behaviors that do not appear to be linear. FIGURE 3 also shows in a and c that the data indicators follow the same trend, whereas b and d show groupings and the difference tends to decrease when congestion levels decrease. Hypothesis test samples obtained from both locations were carried out. For all indicators, the null hypotheses were rejected for both the mean and the variance, evidencing that the congestion levels in the locations are not similar.

The groupings are more evident for the CO1-emissions impacts as shown in the lower row of FIGURE 3. This indicates that, despite the normalization by vehicle-kilometers, there are other factors that affect the Indicator-Impact relationship when comparing across different locations. Similar car fleets, bus fleets and truck fleets and reference levels were assumed both areas to facilitate comparison. Potential arguments for the groupings can be the impact of the topology of the network and traffic signal control modeling, although stronger argument for this difference is the higher percentage of heavy vehicles in Valhallavägen due to the trucks that serve the port of Frihamn.

The analysis continues by considering linear regressions (also visible in FIGURE 3 for the whole sample) and estimating the corresponding R2-value. Given the existing groupings identified above, the R2 values are estimated for a sample composed of both sites, Sankt Eriksplan and Valhallavägen. The results are highlighted using the following formatting: *The table shows the highest R2-value (i.e. most relevant) in bold fonts. The two lowest values R2-value (i.e. less relevant) are shown in underlined italic.*

TABLE 1: R2 values

IMPACT [y-axle]	Both sites					S.Erik					Vallhal.				
	ExD	TTI	RSRwa	RSR_L	SSS	ExD	TTI	RSRwa	RSR_L	SSS	ExD	TTI	RSRwa	RSR_L	SSS
Delay	**1**	*0,900*	0,92	*0,86*	0,96	**1**	0,998	*0,67*	0,99	*0,73*	**1**	0,995	*0,82*	0,97	*0,94*
CO	0,93	*0,707*	**0,96**	*0,67*	0,96	0,87	0,869	*0,79*	**0,88**	*0,79*	**0,98**	0,977	*0,82*	0,96	*0,92*
HC	0,86	*0,605*	**0,92**	*0,57*	0,90	0,65	0,662	*0,60*	**0,67**	*0,52*	0,74	**0,742**	*0,64*	0,72	*0,60*
CO2	0,83	*0,569*	**0,90**	*0,54*	0,87	0,75	0,760	*0,61*	**0,76**	*0,54*	0,52	0,525	*0,48*	**0,53**	*0,38*
FUEL	0,83	*0,572*	**0,91**	*0,54*	0,87	0,76	0,770	*0,62*	**0,77**	*0,55*	0,53	0,536	*0,49*	**0,54**	*0,39*
NOX	0,75	*0,473*	**0,86**	*0,45*	0,81	*0,32*	0,324	**0,36**	0,33	*0,23*	*0,19*	0,190	**0,21**	0,20	*0,10*

As mentioned in section 3.3, 20 random seeds were considered. For estimating the impact of this assumption, similar analyses are repeated with 10 and 50 random seeds. The obtained R2-values did not varied considerably (i.e. $\pm$ 0,01) and highlighting patterns (bold and underlined italic) were the same as in the table shown above. It was then confirmed that the number of replications (i.e. random seeds) does not impact the obtained results.

4.1.1. Comparison across impacts

When comparing impact by impact, it can be observed that, in general, better descriptive capabilities (i.e. higher R2) are obtained for the Delay. This was expected given that the indicators were originally devised for that purpose and the relationship "Delay-congestion indicator" is "encoded" in the equations that describe the performance measure. However, this is not the case for pollutant emissions impacts. It can be observed a there is a large variation in the descriptive capabilities across pollutants. This is mainly caused by the different characteristics required for each emission generation at the engine level. (For example, a car in idle produces high CO2 but low NOx). The descriptive capabilities for NOX of all indicators are poor as it is shown in FIGURE 4 for the three best cases.

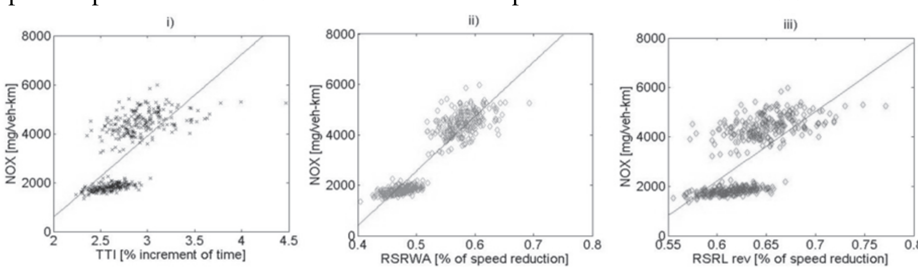

FIGURE 4: Scatter plot: NOX vs. Congestion Indicators (TTI, RSR_{WA}, RSR_L)

4.1.2. Comparison across indicators

Based on the highlighting format used in TABLE 1, it is desirable to have **bold fonts** and not to have *underlined italics fonts* because this indicates low explanatory capabilities. Two analysis situations are considered: i) both sites' results or multiple networks analysis and ii) single site results or single network analysis (considering both sites separately).

- In the whole sample analysis (both sites), the best results are obtained by RSR_{WA} followed closely by ExD and SSS. The results for the other indicators are not desirable.
- In the single site results, the descriptive capabilities of TTI and RSR_L are much better that in the first situation. Whereas RSR_{WA} and SSS show worse descriptive capabilities.

In the case that there is uncertainty about which situation the indicator will be used, and view both situations simultaneously. Then, the only indicator that performs decently in both cases is ExD. Also It is observed that the lowest R2 values of RSR_{WA} (situation ii) are higher than the lowest R2 values of TTI and RSR_L (situation i).

4.2. Statistical confidence

Earlier empirical studies (Morán 2008) identified RSR_L as the most statistically confident indicator given the smaller coefficient of variation ($CV=\sigma/\mu$). Thus, the indicator is efficient, in terms of the required sample size for showing statistical differences. TABLE 2 shows the obtained CV-values in the present study. It can be noted that the CV-values do not vary significantly with the number of replications. It can be observed that RSR_L has significantly smaller CV-values than the other indicators. The same result can be observed graphically in the relevance analysis. FIGURE 4 shows the results for "CO2 versus RSR_{WA}" and "CO2 versus RSR_L".

TABLE 2: Congestion Indicators CV-values for different number of replications

Replications	ExD	TTI	RSR_{WA}	RSR_L	SSS
10	0,240	0,106	0,115	0,055	0,324
15	0,246	0,109	0,115	0,055	0,331
20	0,236	0,103	0,112	0,052	0,321
50	0,241	0,106	0,115	0,053	0,325

In FIGURE4, The x-axis limits are the same for both congestion indicators. The dashed lines indicate the local-mean-values for each simulated area (Sankt Eriksplan in the lower cloud and Vallhallavägen in the upper cloud). The overall-mean-value is shown with the solid vertical line.

Previous empirical studies only had available one observation for each area. This single observation per site corresponds to the local-mean-value. Previous studies showed that the spread of the local-mean-values around the overall-mean-value is smaller for the case of the RSR_L, which in turn gives smaller CV-values.

Given the advantages of simulation and multiple random seeds, the current study had multiple observations per site. These multiple observations correspond to "clouds" around the local-mean-values. FIGURE 5 shows a smaller dispersion of all the observations around the overall-mean-value (solid line) for the case of RSR_L. This in turn results in smaller CV-values as shown in TABLE 2. This advantage, from a statistical point of view, implies a disadvantage from a social relevancy point of view when the areas considered might differ in the percentage of heavy vehicles, given that similar indicator values present different pollutant levels. This diminishes the descriptive capabilities of the indicator when comparing several different areas (even though the descriptive capabilities might perform acceptably for a single area).

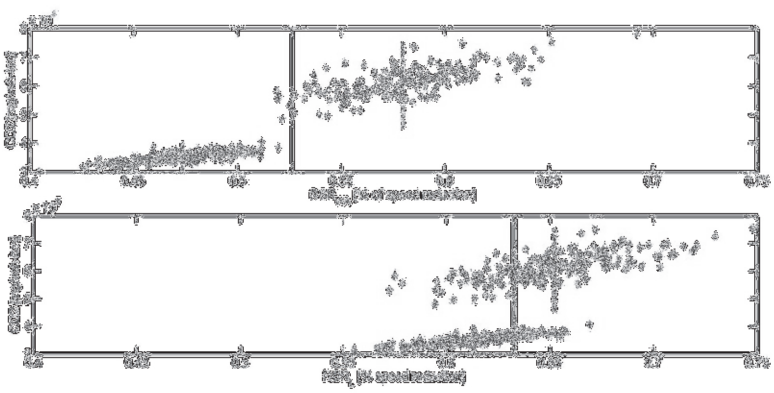

FIGURE 5: Scatter plot: CO2 vs. RSR_{WA} & CO2 vs. RSR_L

5. Conclusions and recommendations

A framework for the analysis of the capability of congestion indicators for describing the traffic and environmental impacts of congestion has been presented. Two approaches for defining congestion have been considered and suitable congestion performance indicators have been described. These indicators have been further developed to enable an analysis using microsimulation that is time dependent and, thus, more sensitive to the dynamics of congestion than earlier studies. The analysis has considered the travel time impacts as well environmental impacts. Regression analyses have been used to identify indicators that better describe congestion impacts (delay and pollutant emissions).

- When considering NOX emissions, none of the indicators performed satisfactorily.
- When considering multiple areas, the indicators that performed better were RSR_{WA} followed by ExD. They showed better descriptive capabilities and they proved to be relatively more robust to local factors. An important local factor that weakened the performance of the other indicators was different percentages of heavy vehicles in the areas.
- When considering single networks where the percentage of heavy vehicles is “locally” constant, the indicators that performed better were TTI, RSR_L, followed by ExD

The selection of a congestion indicator will require information related to the stability of the percentage of heavy vehicles in the areas under study in order to select the most suitable indicator. However, based on the scope of this study (i.e. a time dependent study sensitive to the dynamics aspects of congestion), assuming a percentage of heavy vehicles as being constant across series of 5-minute intervals might be a risky assumption, even for single location. However, when the analyst is sure about this parameter as well as other parameters, e.g. non-variation of topology of the network or data collection methods used for surveying, RSR_L and TTI can be recommended, however RSR_L is preferred due to its statistically confident properties.

6. Discussion and future research

The estimation of the relevance of an indicator, i.e. its capability for describing the impacts of congestion, has been carried out using a simulation model. The vehicle types and the kinematic information obtained from the simulation model are then used to estimate delay and emissions impacts. The estimation of the environmental impacts of congestion is strongly dependent on the capabilities of the emission model. The model MODEM used is dependent on the type of engines considered in its calibration. As the vehicle park changes, the results of this study should be regenerated or reviewed. (Morán 2008)

Linear regression has been previously used when considering disaggregated emission estimations (Shu and Lam 2010). The objective of the present study was to compare different indicators. Considering the same linear approach for all the indicators followed the principle of parsimony. However, the data showed that some indicator-impact relationships were not linear. The development of instantaneous emission models should be focused on examining the true origin of this relationships in order to support other non-linear relationships. It was also observed that for some impacts (for example NOx) that all the congestion indicators showed poor descriptive capabilities. This suggests that other factors should be included when the objective describe a specific pollutant.

All data collection methods inherently consider an aggregation method. The presented analysis used disaggregated data collection allowing to obtain results that are “not affected” by the inherent aggregation method. Further research needs to focus on the impacts caused by each specific data collection method. Special emphasis needs to be placed in the upcoming mobile data collection methods and ubiquitous detector technology currently under development for traffic monitoring.

7. References

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