Unambiguous metrics for evaluation of traffic networks

Robbin J. Blokpoel, Daniel Krajzewicz and Ronald Nippold

Abstract—**This paper presents an extensive set of unambiguous metrics that can be used for evaluation of new ITS applications. Currently in the literature most authors define their own metrics and small differences in definitions can lead to confusion when comparing the results. To derive the set of metrics presented in this paper, several steps have been taken. First, a list has been made with all metrics known by the research partners. Afterwards, a set of base measures has been defined. Using that set, clear formulas for all metrics have been derived and are reported in this paper. Finally, an application example about a cooperative traffic light controller is given.**

III. Introduction

To evaluate new developments in the ITS world it is important that every evaluation uses the same set of metrics and that those metrics are calculated in the same way. Choosing the right metric for the evaluation of a certain situation is also important and not always as trivial as it might seem.

Currently, many papers define their own metrics and give them a name that is logical to the author. A reader who is comparing the work of several authors has to be cautious because the same terminology in one paper might have a different meaning in another paper. For example in [1] the total travel time is defined as: "The *total time spent* is the sum of the *total travel time* and the *total waiting time*". The total travel time does not include the time vehicles have been queued. In [2], on the other hand, the total travel time is the same as was defined as total time spent in [1].

Even a well-known metric in the ITS world like the total travel time has ambiguous definitions in the literature. Due to this, an inattentive reader can easily misinterpret results. When using the definition of total travel time of [1] for evaluating a priority application with speed advice [3], the results can look much different than when the definition from [2] is used. The total travel time including queuing time will probably decrease because there is priority, but the total time the vehicle was driving may very well increase. This is because often an advice to slow down will be given in order to prevent a stop. Effectively, queuing time will be exchanged for driving time, but a reader might conclude that the application is just performing badly. Therefore using the same name for every metric is important to prevent misunderstandings.

Another important factor for the unambiguous use of traffic evaluation metrics is that the definition should be clear. In [1], for example, phrases are used to describe the metrics and [2] even assumes that the reader knows what the author's definition was. The only way to find out those definitions is to compare the values of the various metrics used in that paper.

Because of both the ambiguity in the literature and the lack of clear definitions, it was decided in the European Commission subsidized project iTetris to define them during the project. In iTetris an open platform for testing cooperative applications on a large scale is developed, so proper metrics are essential. This paper describes this extensive set so that they can also be used for other research projects. A more complete report of this can be found in [4].

IV. Definition method

The procedure to define the metrics was divided in several steps. First of all, there are viewpoints from which a traffic network can be evaluated. The most important should be identified and used in the process of defining the metrics. On a road network there are different stakeholders with different values. The individual road user just wants its own journey to be as quick and economic as possible, while for public transport also predictability is very important. Traffic managers and road operators aim to combine the goals of all the road users and try to minimize noise and pollution caused by emissions as well. In the iTetris project the Commune of Bologna has been a representative of this group of stakeholders. Another important view on road networks is the development phase of traffic light control programs and traffic management systems. From this point of view specific metrics are important for traffic engineers to tune the road network in order to achieve the higher level goals given by road operators. Peek Traffic has represented the viewpoint of both traffic engineers and ITS researchers in this definition process. The ITS researchers are of course very significant in this process as well, since the metrics will be used for evaluation of new ITS processes. DLR is an institute specialized in research and represents both the research and the simulation angle to this problem, since they are extending the open source simulation program SUMO for use in the iTetris project. Simulation usually is the only way to really test new ITS applications on a larger scale, since most new technologies are not widely spread yet. With these three partners in the iTetris project, all important

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Robbin J. Blokpoel is traffic engineering researcher at Peek Traffic, Basicweg 16 PO box 2542, 3800 GB, Amersfoort , The Netherlands (tel: +31 334541731; e-mail: robbin.blokpoel@peektraffic.nl).

Daniel Krajzewicz is working on traffic simulation at the Institute of Transportation System at DLR, Rutherfordstr. 2, 12489 Berlin, Germany (tel: +49 30 67055273; e-mail: Daniel.Krajzewicz@dlr.de).

Ronald Nippold is a traffic engineering researcher at the Institute of Transportation System at DLR, Rutherfordstr. 2, 12489 Berlin, Germany (tel: +49 30 67055263; e-mail: Ronald.Nippold@dlr.de).

angles to review ITS systems are represented. Another advantage is that they are all from different countries, so that the work will not be biased towards the habits in one specific country. Commune Bologna is from Italy, Peek Traffic from the Netherlands and DLR from Germany.

The next step was to identify together with all the partners a complete list of all traffic metrics known to them. At first it's not important if there would be overlapping metrics. This is to let the partners be as free as possible in order to get the list complete. After all metric suggestions were collected, the list was consolidated and overlapping metrics removed or adapted.

The consolidated list was categorized in static and dynamic parameters and intersection and network wide parameters. Static parameters are often about road topology and intersection layout, important to be documented so that the results of the dynamic metrics can be seen in a proper perspective. The dynamic ones on the other hand are more affected by ITS technologies and will get more attention.

After consolidation of the list a ranking procedure was done to determine which metrics are most relevant for all the partners. Every partner ranked all metrics on the list with a score of -2 to +2. Those scores were averaged and the ones with a relevance above 0.5 were kept..

For the actual derivation two steps were taken, definition of base measures and derivation of the formulas for the metrics as a function of those base measures. Key in this process is to have a solid set of base measures, even though they might appear quite trivial at first sight, it is important to have unique symbols and definitions for them.

As a last step the computability in the simulation package SUMO is checked for all metrics, this gives better insight in the usage of the metrics.

V. RESULTING METRICS

A. Metric listing

When asking the three partners to sum all metrics known by them, the result was a list with 42 different metrics. Some were overlapping, but doubles were already removed from this number. Most overlap occurred with the different levels of aggregation. For example, for waiting time one can define four different, but overlapping metrics: Mean waiting time, aggregated for all vehicles and divided by the number of vehicles; total waiting time, also aggregated over all vehicles, but not divided by the number of vehicles; mean and total waiting time at a specific location. When a clear definition for either of those waiting times is available, the other three can be derived easily by either only taking vehicles on a specific location into account or multiplication/division by the total number of vehicles. This kind of overlap also occurs for other metrics like travel time, speed and time lost. Therefore in this paper only the mean value of such a metric will be considered for the entire network.

In Table 1 the list of consolidated metrics is presented. In this table it is also indicated if a certain metric is static or dynamic. Some metrics are still only for a specific area, but then it's because they are only applicable to such a specific area. The cycle time, for example is usually intersection specific, so a network-wide cycle time wouldn't make sense. The same holds for the maximum queue length per cycle and mean queue length in front of an intersection. As can be seen from the table, 29 metrics were left after consolidation.

TABLE 1
CONSOLIDATED LIST OF METRICS

Measure	dynamic	static
mean travel time	x	
mean speed	x	
mean waiting time	x	
mean loss time	x	
mean number of lanes per street		x
mean number of parking processes	x	
mean number of delivery processes	x	
mean number of stops of public transport vehicles	x	
mean number of stops	x	
mean fuel consumption	x	
mean noise/exhaust/other emissions	x	
number of accidents and type of accident	x	
number of level-free crossing for pedestrians, bicycles		x
number of guide ways for specific turning directions at intersections		x
number of signal controlled intersections		x
mean parking space/ loading bay search delay	x	
connection to different modes of transport / P&R		x
number of one-way-streets / dead-end-streets		x
potholes, road surface, paving		x
number of route alternatives		x
level / quality of road signing		x
LOS (level of service)	x	
mean distance traveled	x	
route distribution (intensity and travel time)	x	
network saturation (I/C-ratio)	x	
mean queue length in front of the junction	x	
delay between traffic lights	x	
cycle time	x	
maximum queue length per cycle	x	

B. Metric ranking

With the list of Table 1 completed, the next step was to rank the metrics. The least relevant for ITS application evaluations will be described in this section; the others will be derived and more precisely described in the remaining of this chapter.

The mean number of parking processes and delivery processes were ranked as neutral on average. Although they are important boundary conditions for ITS loading bay and parking spot reservation systems, they cannot be measured from simulations. They are inputs for simulations instead of metrics for which an ITS application can make an improvement, and should be acquired from counting on the real street network. Another closely related metric - the mean parking search delay - can be used though. More on that can be found in the next section.

Then there is a set of metrics that was classified as neutral or even irrelevant which all have to do with the road network topology. Again these are more like boundary conditions instead of a metric that can be the objective for an ITS application to improve. These are the number of level-free crossing for pedestrians and bicycles; the number of signal controlled intersections; connections to different modes of transport / P&R; the number of one-way-streets / dead-end-streets; potholes, road surface, paving; level / quality of road signing. Some of these factors are commonly processed in the saturation flow, which in its turn can be calculated per lane or per road. Weather also influences the saturation flow, so even though in a simulation it seems to be a static factor, in reality it can be dynamic. More on saturation flow can be found in the base measures section.

With traffic management, certain static factors like the number of lanes on a street or guide ways for a specific turning direction on an intersection and the number of route alternatives can be made dynamic. Those factors are very situation specific and should always be described in a detailed manner. Because of this, there is no need to define metrics for it and it is not surprising that these metrics were ranked at a relevance of only slightly above 0.

C. Base Measures

In this section the base measures are defined, they will serve as building blocks for the actual metric definitions. Some can also serve as the definition for boundary conditions. Table 2 shows all base measures and below the table clarifying comments are given.

TABLE 2
BASE MEASURES DEFINITION

t_s^{beg}	the time at which scenario *s* begins (its first simulation step, in [s])
t_s^{end}	the time at which scenario *s* ends (its last simulation step, in [s])
n_s^{vehs}	(number of) vehicles simulated within scenario *s* (number of vehicles which entered the simulated area during the simulation run)
$n_{s,t}^{\text{vehs}}$	(number of) vehicles within the scenario *s* at time *t*
n_i^{vehs}	(number of) vehicles which were in front of the intersection *i* during the simulation's run
$n_{i,t}^{\text{vehs}}$	(number of) vehicles which are in front of the intersection *i* at time *t* (see comment 1)
$n_{tl1,tl2}^{\text{vehs}}$	(number of) vehicles which pass traffic light *tl1* and traffic light *tl2* (in this order)
n_r^{vehs}	(number of) vehicles which use route *r*
n_i^{lanes}	(number of) lanes which end at intersection *i*
$v_{veh,t}$	velocity of vehicle *veh* at time *t* (in [m/s])
t_{veh}^{depart}	the time at which vehicle *veh* enters the simulated network (in [s])
t_{veh}^{arrival}	the time at which vehicle *veh* leaves the simulated network (in [s])
t_{veh}^{travel}	the travel time of vehicle *veh* (in [s]) (see comment 1)
d_{veh}^{route}	the distance between a vehicle's starting and ending position (in [m])
t_{veh}^{waiting}	the sum of seconds at which vehicle *veh* was halting (in [s]) (see comment 2)
$n_{l,t}^{\text{waiting}}$	the number of vehicles halting on lane *l* at time *t* (see comment 2)
n_{veh}^{stops}	the number of stops started by vehicle *veh* (see comment 2)
$n_{l,t}^{\text{stopbegin}}$	the number of vehicles starting to halt on lane *l* at time *t* (see comment 2)
$e_{veh,t}^{\text{x}}$	emissions of x generated by vehicle *veh* at time *t* (in [g/s]; x: CO, CO_2, HC, PM_x, NO_x)
$c_{veh,t}^{\text{fuel}}$	fuel consumption of vehicle *veh* at time *t* (in [l/s])
$e_{veh,t}^{\text{noise}}$	noise generated by vehicle *veh* at time *t* (in [dBA])
$e_{lane,t}^{\text{noise}}$	noise generated on lane *l* at time *t* (in [dBA])
$l_{l,t}^{\text{queue}}$	the length in front of a traffic light *tl* on lane *l* at time *t* (in [m]) (see comment 3)
$t_{tl,cy}^{\text{cyclebegin}}$	the time cycle *cy* of the queue *q* starts (in [s]) (see comment 4)
$t_{sg,cy}^{\text{cycleend}}$	the time cycle *cy* of the signal group *sg* ends (in [s]) (see comment 4)
$t_{veh,tl1,tl2}^{\text{freeflow}}$	the time vehicle *veh* needs to pass traffic light *tl2* counted from the time it passed traffic light *tl1* under free flow conditions (no interactions with other vehicles and obeying maximum speed limit, in [s])
$t_{veh,tl1,tl2}^{\text{congested}}$	the time vehicle *veh* needs to pass traffic light *tl2* counted from the time it passed traffic light *tl1* under regarded traffic condition (in [s])
$n_s^{\text{intersection}}$	the number of intersections in scenario *s*

1) Travel Time

Please note that the travel time is defined only for vehicles which have entered and left the simulated area. Otherwise a bias will occur as a function of the length of the simulation/ measurement. Since vehicles which did not leave the network have a lower travel time than they should have simply because they didn't finish their route yet. Then travel time can be computed as follows:

$$t_{veh}^{\text{travel}} = t_{veh}^{\text{arrival}} - t_{veh}^{\text{depart}} \quad (3)$$

2) Stopped Vehicles

A vehicle is counted as "waiting" or "stopped" if its speed is lower than 5km/h and the distance to its leading vehicle or a stopline is less than 5m. This definition is needed to distinguish between vehicles standing in a jam and vehicles which want to halt (for example for parking). Also, this definition sets a certain threshold for the speed at which a "jam" begins. Please note that "waiting", "stopped", and "in jam" are treated equally here. This definition of a jam respects measures used by the Community of Bologna. The speed limit of 5km/h is required because some drivers tend to drive really slowly forward from time to time while waiting at a traffic light.

3) Queues in front of Intersections

Computing the longest queue in front of an intersection may become non trivial if there are more directions a vehicle can go to after passing a stopline. Here, it must be decided whether all incoming traffic streams must be counted or only the maximum one. Because this measure is also used for optimizing traffic lights, it was decided to use the sum of all streams that arrive at one lane of an intersection.

4) Cycle time

The cycle time is a measure that seems to be rather trivial. Simply measure the time between the moments a certain signal group gets green according to [5]. However, since traffic light programs can be very dynamic it is not always clear what the cycle time actually is. The signal group that is monitored for measuring the cycle time might be skipped from time to time when there is no traffic, or the length of other phases varies in such a way that the cycle time changes differently for different signal groups. Therefore the signal group for which the cycle time measurement was done should always be noted.

D. Metric definition

With the complete set of metrics in Table 2, it is now possible to derive formulae for the metrics. The results are shown in Table 3. Again below the table clarifying remarks will be given.

TABLE 3
METRIC DEFINITION

mean travel time (see comment 1)
$P_s^{\text{travel time, mean}} = \frac{1}{n_s^{\text{vehs}}} \sum_{n=1}^{n_s^{\text{vehs}}} t_n^{\text{travel}}$
mean speed (see comment 1)
$P_s^{\text{velocity, mean}} = \frac{1}{\sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \lvert n_{s,t}^{\text{vehs}} \rvert} \sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \sum_{v \in n_s^{\text{vehs}}} v_{v,t}$
mean waiting time (see comment 1)
$P_s^{\text{waiting time, mean}} = \frac{1}{\lvert n_s^{\text{vehs}} \rvert} \sum_{v \in n_s^{\text{vehs}}} t_v^{\text{waiting}}$
mean number of stops (see comment 1)
$P_s^{\text{stops, mean}} = \frac{1}{\lvert n_s^{\text{vehs}} \rvert} \sum_{v \in n_s^{\text{vehs}}} n_v^{\text{stops}}$
mean loss time (see comment 2)
$P_s^{\text{loss time, mean}} = P_s^{\text{travel time, mean}} - P_s^{\text{free flow time, mean}}$
mean fuel consumption (see comment 1) $P_s^{\text{fuel consumption, mean}} = \frac{1}{\sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \lvert n_{s,t}^{\text{vehs}} \rvert} \sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \sum_{v \in n_{s,t}^{\text{vehs}}} c_{v,t}^{\text{fuel}}$
mean exhaust emissions (for pollutant x) (see comment 1) $P_s^{\text{exhaust emission, mean}} = \frac{1}{\sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \lvert n_{s,t}^{\text{vehs}} \rvert} \sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \sum_{v \in n_s^{\text{vehs}}} e_{v,t}^{\text{x}}$
mean distance travelled (see comment 1)
$P_s^{\text{distance, mean}} = \frac{1}{\lvert n_s^{\text{vehs}} \rvert} \sum_{v \in n_s^{\text{vehs}}} d_v^{\text{route}}$
network saturation (I/C-ratio) (see comment 3)
$P_s^{\text{saturation}} = \frac{1}{\lvert n_s^{\text{intersection}} \rvert} \sum_{i \in n_s^{\text{intersection}}} P_i^{\text{saturation}}$
mean queue length in front of the junction
$P_i^{\text{queue, mean}} = \frac{\sum_{t=t_s^{\text{beg}}}^{t_s^{\text{end}}} \sum_{l \in n_i^{\text{lanes}}} l_{l,t}^{\text{queue}}}{\left(t_s^{\text{end}} - t_s^{\text{beg}}\right) \cdot \lvert n_i^{\text{lanes}} \rvert}$
mean noise emissions
(See comment 4)
number of accidents
(See comment 5)
LOS (level of service)
(See comment 6)
route distribution (intensity and travel time)
(See comment 7)
mean parking space/ loading bay search delay
(See comment 8)

1) Aggregation

Often, aggregated values show the benefits of a new system at once – the lower the mean travel time, or the higher the mean speed, the better the performance.

Nonetheless, a net-wide aggregation of the values holds some pitfalls. Because all simulated vehicles' measures are aggregated, incidents which affect only a small part of the network or methods for resolving such may get invisible, because they are affecting only a small fraction of a day's traffic. Additionally, it may happen that effects in opposite directions – like travel time reduction and increase – are not noticed because they cancel each other out. Also, aggregation over a complete simulation execution time removes time-dependant changes of the values.

To avoid such problems, other aggregation types have proved to be valuable:

- aggregating data within specific time-windows.
- aggregating data only for certain origin/destination pairs or certain routes.
- aggregating data distinguishing between vehicles that are equipped and not equipped with te cooperative application.

Of course, the named aggregation types can be combined.

Additionally, it is recommended to incorporate the variances or standard deviations of the aggregated measures. This is important because the standard deviation tells something about the predictability of the metric for an individual road user. For example most road users would prefer a travel time of 100 seconds with a standard deviation of 5 seconds over one of 95 and a standard deviation of 60 seconds. More about statistics can be found in [6].

2) Loss time

A loss time is a very valuable measure, though it is hard to measure. The exact definition is given in the table, but sometimes the free flow travel time is not available. Then as an alternative, the loss time per intersection to intersection connection can be calculated. This results in the following formula:

$$t_{veh,tl1,tl2}^{\text{loss}} = t_{veh,tl1,tl2}^{\text{congested}} - t_{veh,tl1,tl2}^{\text{freeflow}} \quad (2)$$

Basically this is applicable for any path or time slot, but it is advisable to let the intersection to intersection intervals start and end just after a stop line. Starting an interval just before a stop line gives offsets to the travel time for the position of the vehicles in the queue and does not give a good impression of the intersections performance.

3) Intersection saturation

The saturation of a (controlled) intersection is the mean of the participating streams' saturation, where a "stream" is a connection between an incoming and an outgoing road. More than one incoming lanes may contribute into one stream, and a single incoming lane may be the origin of more than one stream.

The saturation of a stream is its usage divided by its assumed capacity:

$$P_i^{\text{saturation}} = \sum_{t=t_i^{\text{beg}}}^{t_i^{\text{end}}} \frac{\left| n_{\text{t}}^{\text{veh, enter stream}} \right|}{capacity^{\text{stream}}} \quad (3)$$

Where $\left| n_{\text{t}}^{\text{veh, enter stream}} \right|$ is the number of vehicles that approach the stream *s* (enter one of the lanes that belong to this stream for example) at time *t* and $capacity^{\text{stream}}$ is the stream's capacity – including the green ratio of the traffic lights.

4) Mean Noise Emissions

Please note that the noise produced by a single vehicle must not be summed or aggregated as other values. Plain addition/computation of a mean value could be done but does not correspond to the sound perception (see [7] for more details).. Due to this, it is recommended not to use sound emissions on a network-wide level, but rather investigate single roads' sound levels and compare their changes.

5) Number of Accidents and Type of Accident

Hardly any microscopic simulations are able to predict the number of accidents. However, if it is available it is just a matter of counting. It should be noted that since accidents are very rare, many simulations or a long measuring interval in real situations are required to acquire statistically significant data.

6) Level of Service

Here, the definition from Community of Bologna is used. The service level is computed using a look-up table, as shown in Table 4. The input value is the mean total loss time per intersection. For a net-wide application, the mean value of all simulated traffic lights' delay values is computed and then used for the look-up. Note that these values are subjective and can vary per city.

TABLE 4
SERVICE LEVEL LOOKUP TABLE USED BY COMMUNE BOLOGNA

Mean total loss time per intersection	**Resulting Service Level**
<5s	A
>5s and <10s	B
>10s and <20s	C
>20s and <30s	D
>30s and <45s	E
>45s	F

7) Route Distribution

When traveling through a road network, many route alternatives with the same start and finish node are possible. The measure "route distribution" asks for both the intensity and the travel time on a certain route. The probability that each of the possible routes is used can be computed using:

$$P_{b,e}^{\text{route usage}} = \frac{n_r^{\text{veh}}}{n_{b,e}^{\text{routes}}} \quad (4)$$

Where $n_{b,e}^{\text{routes}}$ is the set of all possible routes between road *b* and road *e*. The travel time corresponding to that route can be calculated with the formula given in Table 3 and aggregated over that specific route.

8) Mean parking space/ loading bay search delay

This is a special case of a loss time. Since many new ITS applications deal with parking space or loading bay reservations, special attention should be paid to this. The search delay can be defined as the actual travel time minus the travel time when the car would have gone straight to the free parking spot. In practice this is hard to measure and in simulation one would have to define three scenarios: with predefined parking search routes, the original situation; a scenario with perfectly pre-planned routes directly to the correct parking spot, the reference "free-flow-like situation" and a situation with the ITS application under test active. Then the loss times can be compared well.

VI. APPLICATION

To give an idea about proper application of the metrics derived in the previous chapter, an example situation will be discussed in here. This example is about the cooperative traffic light controller developed in the iTetris project. More details can be found in [8].

The goal of the traffic light controller is to have the same performance as state of the art control strategies and at the same time offer cooperative services. To validate the algorithm, it has been implemented in the traffic light controllers of a micro simulation of the city of Bologna. Both total travel time and total waiting time have been measured for all vehicles and were used to compare the performance of a fixed time and a vehicle actuated controller. The results are presented in Figure 1.

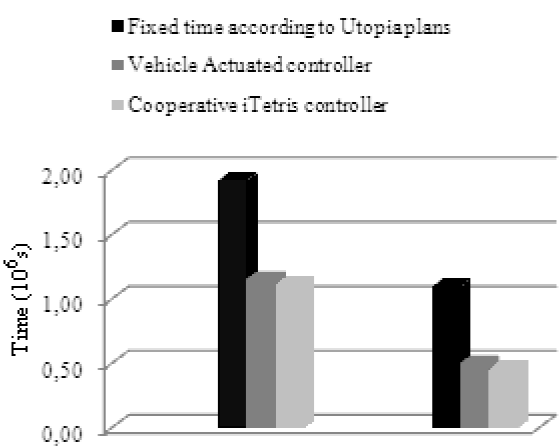

FIGURE 1: COMPARISON OF TRAVEL TIME (LEFT) AND WAITING TIME (RIGHT)

This comparison directly shows the importance of the choice of the metric. For total travel time the difference is about 40% between the fixed time and the vehicle actuated strategy, while for the waiting time the difference is 56%. Also the difference between the vehicle actuated controller and the cooperative controller changes from 6% to 9%.

The example also clearly shows that the waiting time is not equal to the loss time. By definition the total free flow travel time should be the same for all controllers, but the difference between waiting time and total travel time is between 0.6 10^6 and 0.8 10^6 seconds. This can be explained by the fact that vehicles usually slow down more when they are about to enter a large queue. Having to stop twice for the same traffic light also contributes to this. In this case there is additional time that vehicles have to slow down and accelerate.

The cooperative services of this controller will be tested in a later phase of the project. For the speed advice application the difference between loss time and waiting time will probably show to be even more important, because vehicles are advised to slow down in order to pass through green without stopping. That way, waiting time is converted into driving slower. When only waiting time would be considered the results will probably look too positive. More important will be to check for the actual objectives of the application, reduce CO_2 emissions and stops. For both are metrics derived and they will certainly be used. For cooperative priority services the standard deviation is also very important to make travel times more predictable.

VII. CONCLUSION

This paper showed an extensive list of metrics derived with a systematic method. By first defining strong base measures, it was possible to derive clear formulas for most metrics as shown in Table 4.

The application chapter shows an example of the differences between travel time, loss time and waiting time. These are metrics from the same spectrum as the ambiguous ones discussed in the introduction. The metrics in this paper are designed to be unambiguous and suitable for evaluating novel cooperative ITS strategies.

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