Empirical Analysis of an In-car Speed, Headway and Lane use Advisory System

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\textbf{ABSTRACT}

For a recently developed in-car speed, headway and lane use advisory system, this paper investigates empirically advice validity (advice given in correct traffic circumstances), credibility (advice logical to drivers) and frequency. The system has been developed to optimize traffic flow by giving advice on a tactical scale. This scale allows traffic flow improvement and fills a gap as most ITS which aim to optimize traffic flow operate on the operational or strategic scale. Using log files of the actual system for a period of two weeks, the validity, credibility and frequency of advices is determined. Validity is not guaranteed as the advices are determined based on a predicted traffic state due to data delay and as the advices are based on the predicted traffic state 1 minute in the future. Given that the advisory system is a first in its kind, a new methodology was developed to assess the system, based on the use of virtual trajectories and defining indicators to assess, validity, credibility and frequency. The analysis shows that many advices are indeed valid and credible, but some are not, allowing room for improvement. Advice frequency is found to be reasonable. The analysis also shows that in-car filtering of advices, i.e. merging equal advices, is important to lower the frequency.

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INTRODUCTION
In recent years Intelligent Transport Systems (ITS) have gained attention and are increasingly used to improve traffic efficiency, safety and comfort. Many types of ITS exist and Advanced Driver Assistance Systems (ADAS) refers to in-car systems that help the driver with various tasks. Examples are Adaptive Cruise Control (ACC), or the more advanced Cooperative Adaptive Cruise Control (CACC) where vehicles share information. These systems take over a specific task of the driver (i.e. car-following), but ADAS can also be warning or informative. Intervening systems, which take over a driving task, have been shown to have the potential to reduce travel time delay considerably, such as for example Congestion Assistance [1], where a 30% reduction of delay can already be found at 10% penetration rate.

Other ITS systems try to optimize traffic flow (or individual travel times) by for example road-side route guidance [2] or in-car route guidance [3]. What is striking is that most ITS therefore either work on the operational scale (vehicle control) or on a strategic scale (routing, departure). Hence, they neglect the potential for traffic flow improvement at the tactical scale (lane selection, adjusting to downstream conditions). Moreover, the tactical scale allows advisory systems, whereas advice on the operational scale is not feasible due to overloading the driver. Therefore, a system has been developed that gives in-car advice on the tactical scale, by using existing technologies. This makes this class of systems a feasible next step towards a more automated vehicular traffic system.

This paper presents the system which has been implemented on a single vehicle and which has been thoroughly assessed using simulation [4]. Here, the validity and credibility of different advices that the system gives is tested by processing log files that the system generated while running for two weeks. During this period, no equipped vehicle was present on the road, but detector data was gathered and advices were derived. The validity and credibility are assessed. The latter is an important aspect since it influences compliance. Also, this paper uses advices that are derived based on the actual system (i.e. empirical rather than simulation) which allows an evaluation of how the system operates in reality. The methodology to derive advice validity and credibility is to create virtual trajectories and determine several indicators for the advices that these trajectories come across. This methodology, including the indicators, is an important contribution due to the unique nature of the advisory system.

Besides validity and credibility of the advices, this paper will also look at the advice frequency. To this end, the amount of advices drivers may receive is determined for different times of different days. A simple virtual in-car advice filter which merges equal and consecutive advices is implemented to lower the amount of advices that are given, i.e. it lowers the advice frequency.

The paper is structured as follows. First, the in-car advisory system is presented. Next, the methodology of how the log files are processed into indicators from which advice validity and credibility can be derived is discussed. In the next chapter the results are shown, after which the last chapter gives discussion and conclusions.

IN-CAR ADVISORY SYSTEM
The philosophy of the system is to give drivers advice on the tactical scale, i.e. with regard to the traffic state they will reach in 1 minute, on headway, speed and lane, with the aim to improve traffic flow efficiency on key locations where regular driver behavior is sub-optimal. In this way, traffic flow can be improved without overloading drivers with advices. The system has been implemented and tested in simulation [4], and is found to show traffic flow improvements as
travel time delay can be reduced up to some 40-50%. The system is explained in detail in [4]. The general setup of the system is provided in figure 1. Both floating car data from equipped vehicles and loop detector data are gathered at the traffic management centre. There, the data is used to perform traffic state estimation and prediction. Using the predicted traffic state, the advice algorithm determines advices and sends them to individual drivers.

**FIGURE 1** Overview of the in-car advisory system.

The system can give the advices as listed below. The latter three are qualitative advices, i.e. no value for headway or speed is provided, as this pertains directly to the desired behavior or because drivers are unable to maintain a quantitative advice [5].

- Change lane to the left or right, or keep lane.
- Drive at given speed.
- Synchronize speed to left/right lane.
- Yield for merging traffic from the left/right lane.
- Maintain a short but safe headway.

The traffic state estimation and prediction algorithm is based on the Adaptive Smoothing Method (ASM) [6] which is performed on lane level rather than road level. This allows the traffic state to be determined on individual lanes allowing lane advices. Although the ASM is designed as an interpolation filter, here it is used as an extrapolation filter as the traffic state for 1 minute ahead is estimated. Furthermore, as no equipped vehicles were on the road during the evaluated period and as detector data is delayed with 75s, the ASM is also used to span this delay. The system is able to combine different data sources using a method which is highly similar to the Extended Generalized Treiber-Helbing Filter (EGTF) [7], where different data sources get different weights depending on their reliability, but in this paper only detector data is used.

The advice algorithm derives advices based on the predicted traffic state. It performs 4 steps:

- Assigning infrastructural properties to the cells of the predicted traffic state. This information can be used to derive advices, e.g. give way to merging vehicles at a lane-drop.
- Performing different advice principles. Different advice principles can be attached to the advice algorithm, and these are performed independently. The role of an advice principle is to determine a set of advice regions. Each region defines where and when certain
advices are given. A region may hold multiple advices, though vehicles will be selected to receive only one of the advices. Two advice principles will be discussed here.

- Filtering the advices. Since the different advice principles operate independently, advice regions may overlap. Therefore, this step filters advices where they overlap with a simple priority order based on the type of advice that is given.
- Selecting users for different advices. User selection may be based on the destination of users (if known) and on a moving average of the reported speed (as an indication of the order of desired speed between users).

Two advice principles have been used: acceleration advice and distribution advice. They will be discussed in the next two sections.

**Acceleration advice principle**
This advice principle is aimed at reducing the capacity drop. Many causes for the capacity drop have been mentioned in literature such as lane changes [8]-[9] and bounded acceleration [10]. Here it is assumed that an important contribution is formed by a reduced activeness of the driver which may lead to a lower responsiveness to an accelerating leader as well as to larger desired headways on average [11]. Therefore, before drivers reach the end of congestion they may be advised to maintain a short but safe headway. Effectively this will increase their acceleration, though drivers are not directly advised concerning the acceleration. This advice is indicated in figure 2a.

**Distribution advice principle**
The goal of the distribution advice principle is to redistribute traffic over the lanes in situations where one lane is particularly busy, while other lanes have spare capacity. Typically, this is true when congestion starts [12]. Furthermore, congestion may start on the busiest lane through disturbances. One type of disturbance is formed by lane changes [13], though other disturbances may also cause congestion such as for example speed reductions at uphill sections [14]. The distribution advice principle tries to reduce lane change disturbances. It does so by advising
drivers to synchronize their speed before a lane change, or to give way for merging vehicles, if it can be assumed from the infrastructure that lane changes will be performed. This can be seen in 4 of the 5 examples in figure 2b. If there is no infrastructural reason for lane changes, drivers are advised to keep a more stable speed than their current speed on the busy lane.

METHODOLOGY
This chapter describes how the validity, credibility and frequency of advices is derived from the log files of the advisory system. The system ran for two weeks from February the 11th till the 24th of 2013, during which no exceptional circumstances were present. Advices were generated for a 10km stretch on the A20 freeway, from Prins Alexander (Rotterdam) to Gouda, see also figure 3. The general concept is that virtual trajectories are derived for which statistics are gathered that allow us to analyze advices as encountered by these virtual vehicles.

FIGURE 3  A20 network with distances and detector locations in meters.

The general concept of the methodology is shown in figure 4. The system logs its operations, including the detector data and the generated advice regions. From the detector data, the traffic state is estimated. This estimation is ex-post, i.e. all available data is used (rather than delayed data only in the live system). Next, the traffic state is used to derive virtual trajectories. The trajectories are compared with the advice regions, and a number of indicators for advice validity and advice credibility is derived concerning the advices a vehicle following the trajectory would have received.

FIGURE 4  Overview of the methodology for the empirical evaluation.

Available log data
Among information about the state of the advisory system, the log files contain the incoming data and the generated advices. Since the system ran without equipped vehicles on the road, no floating car data is available. Dual loop detector data is available and contains 1 minute aggregated flow and arithmetic mean speed, including location and time.
The advice data concerns advice regions rather than individual advices (as no vehicles with the system were on the road) which includes the following information:

- Valid range, including the lane, and valid time span.
- Which qualitative advices were active (synchronization, yielding, short headway).
- Advised speed (if any).
- Advised lane (if any), which may or may not be equal to the current lane.

**Ex-post traffic state estimation**

Using the detector data from the log files, the traffic state on the freeway stretch can be estimated. Similarly as for the prediction method of the advisory system itself, we used the ASM at lane level to derive the traffic state. Just as with the actual system, this ignores lane changes, especially influencing flow. However, with closely spaced detectors and by the use of all data, this error is expected to be small enough for the empirical evaluation. The used cells have a length of $\Delta x = 100m$ and a time span of $\Delta t = 10s$. Other parameters are the free flow propagation speed $c_{free} = 85km/h$, the congestion propagation speed $c_{cong} = -18km/h$, flip-over speed between congestion and free flow $V_c = 80km/h$, flip-over region width $\Delta v = 10km/h$, spatial kernel width $\sigma = 300m$ and temporal kernel width $\tau = 30s$. Within each cell, the traffic state is assumed to be homogeneous and equal to the state as derived with the ASM for the center of the cell. Similarly, the middle of the aggregation period of the detector data was used.

**Virtual trajectories**

Virtual trajectories are required since no equipped vehicles were on the road, while the driver perspective is vital for determining advice credibility. Methods to derive trajectories from detector data are readily available in literature [15]-[16], and are often used for travel time estimation. In [15] and [16] a number of trajectory estimation methods are compared, and the more complex methods outperform the simpler methods. In [16] a method is presented which uses the EGTF [7] to interpolate underlying data to a finer grid than that of e.g. detector data.

Since the traffic state from the traffic state estimation using the EGTF is already available in the empirical analysis, the use of the filtered trajectory estimation method is straight forward, and the used method is essentially equal to the method described in [16]. Since this method performs best, it is chosen. The algorithm to describe how trajectories are derived using the EGTF speed field will be described next. An important difference with the description in [16] is that each cell has a representative speed derived at its center in space and time. The comparison in [16] considers cells (i.e. sections) in between measured (or in this case estimated) locations, which is equal to simpler methods dealing with detector data. Consequently, in our case no interpolation of any sort is required within a single cell, and speeds are assumed to be obtained instantaneously when entering the next cell.

For each considered day and for each lane, the first coordinate of the $n^{th}$ trajectory has $x_0 = 0$ (the start of the network) and $t_0 = (m-1)\cdot\Delta T$, where $\Delta T$ is the time difference between trajectories which is set at 5 minutes. The algorithm to find the next coordinate $(x_{n+1}, t_{n+1})$ based on the current coordinate $(x_n, t_n)$ is given by equation (1) and visualized in figure 5. It describes that the next coordinate is restricted by the next cell boundary in either space or time. Lane changes are not considered.
In equation (1), \( x'_n \) is the location of the first cell boundary downstream of \( x_n \) and \( t'_n \) is the time of the first cell boundary after \( t_n \). With the speed \( v \) inside the cell, two times are derived being the time until \( x'_n \) is reached, given by \( t_x = (x'_n - x_n)/v \) and the time until \( t'_n \) is reached, given by \( t_t = t'_n - t_n \). Depending on which time is shortest, either boundary defines the next trajectory coordinate. This is displayed in figure 5 for two different values of \( v \) leading to two different next boundaries from the same point \((x_n, t_n)\). Figure 6 shows some example trajectories with the actual data.

![Diagram of trajectory determination](Image)

**FIGURE 5** Determination of the next coordinate in a trajectory.

**Virtual trajectories and advice regions**

With the virtual trajectories, statistics can be gathered concerning the advice validity and credibility. These statistics concern the advice regions, which are available from the system log, that a trajectory encounters. A region is considered to be encountered when a single section of a trajectory, i.e. from \((x_n, t_n)\) to \((x_{n+1}, t_{n+1})\), crosses an entering boundary of an advice region in either space (upstream edge) or time (start time). In this analysis a simple form of in-car filtering is applied, which merges advices if these are equal and encountered consecutively. For the second advice region, the driver does not receive the message again. As such, merged advices are considered as one for the analysis.

In the remainder of this chapter, a distinction is made between the number of encountered advice regions, denoted as the *gross* number of advices, and the number of advice regions that are not filtered by the simulated in-car filtering, denoted as the *net* number of advices. Advice validity and credibility will only be derived for the advices that are not filtered, as these are presented to the driver (the other advices are merged). The effect of in-car filtering is visualized in figure 6, where the net advices are indicated.

Finally, for each trajectory the travel time is also determined in order to evaluate the correlation between travel time and the (maximum) number of advices given of different types,
since certain advices are often given in free flow while other advices are typically given in congestion.

**FIGURE 6** Example trajectories (white lines) on February 12th 2013. These go through the speed field [km/h]. Dashed regions are from the acceleration advice principle and continuous regions are from the distribution advice principle. The continuous arrows indicate the location and time when advices are given and for which advice validity and credibility is determined. The dashed arrows indicate advices that are merged with the previous advice. Note that given the traffic state estimation grid of $\Delta x = 100m$ and $\Delta t = 10s$ the trajectories appear continuous at this scale, but they are piece-wise linear.

**Indicators of advice validity and credibility**

Advice validity and credibility is evaluated for six different advice categories, which are: synchronize, yield, short headway, speed, change lane and keep lane. Given that the acceleration advice principle and the distribution advice principle are used, we can be sure that short headway advices are from the acceleration advice principle while the remaining advices are from the distribution advice principle. The six advice categories cover the complete set of advices that result from the system. For the indicators that are defined for advice credibility, assumptions are made about what drivers would and would not consider as credible in terms of the traffic circumstances they encounter when and shortly after they receive advice.

Part of advice validity is that advices are given in line with the advice principles. In order to gain insight into this, both the spatial and temporal distribution of the various advice categories are derived. The spatial and temporal distributions are separated per lane in order not to obscure effects on individual lanes. The spatial distribution is based on the gross advice regions, whereas the temporal distribution only concerns the net advices encountered with the trajectories. The latter allows the number of advices during different times of the day to be considered for advice credibility.

While the spatial and temporal distributions are important indicators to check whether the advices are in line with the advice principles, and whether the system does not overload drivers with information, other indicators are required to check that the traffic state around an advice is
also in line with the advice principles (for advice validity) and does not present the user with a situation in which a given advice is not credible (for advice credibility). From the perspective of both advice validity and credibility, each of the six categories will use one or more indicators. In total 12 indicators will be used, a) though i). An overview of these indicators, and for which advice category or perspective they are used, is presented in table 1.

**TABLE 1 Overview of validity indicators.**

<table>
<thead>
<tr>
<th>Advice type</th>
<th>Advice validity</th>
<th>Advice credibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change lane</td>
<td>a) Maximum flow in next 2km</td>
<td>c) Current density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d) Density difference with target lane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e) Current speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>f) Speed difference with target lane</td>
</tr>
<tr>
<td>Keep lane</td>
<td>Equal to change lane validity</td>
<td>Equal to change lane validity</td>
</tr>
<tr>
<td>Synchronize</td>
<td>Equal to change lane validity</td>
<td>g) Distance to lane drop</td>
</tr>
<tr>
<td>Yield</td>
<td>Equal to change lane validity</td>
<td>h) Distance to lane drop</td>
</tr>
<tr>
<td>Short headway</td>
<td>b) Distance to end of congestion</td>
<td>b) Distance to end of congestion</td>
</tr>
<tr>
<td>Speed</td>
<td>Equal to change lane validity</td>
<td>i) Current speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>j) Time until next slowdown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>k) Current density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>l) Speed difference with advice</td>
</tr>
</tbody>
</table>

Many of the advice categories stem from the distribution advice principle, and consequently have common advice validity. Essentially all these advices are valid if one lane indeed has a high flow for which advices are required. This validity will only be evaluated for the ‘change lane’ category, but applies to other advice categories as well, as shown in table 1. Similarly, indicators of advice credibility for ‘change lane’ and ‘keep lane’ advice are equal, as the latter is given on the target lane of the first (according to distribution advice principle), i.e. there is one single traffic circumstance for which the target lane is credible to drive on. These indicators are also only evaluated for the ‘change lane’ category. All indicators are derived at the time and location where and when an advice region is encountered by a virtual trajectory. Also, the advice should not be filtered. The indicators, and why they are used, will be discussed next per category.

**Change lane advice**

The advice validity of this advice, as well as a number of other advice categories which are related as they all stem from the distribution advice principle, depends on whether there indeed is a peak flow in the lane where drivers receive advice to change lane. These advices are triggered by an estimated high flow, but due to data delay and other estimation errors this may actually not occur. Advices are given in an area of 2km upstream of the peak flow. Consequently, the advices are valid if the maximum flow in the next 2km of where an advice is given, is indeed high. For this the indicator “a) maximum flow in next 2km” is used. This is derived instantaneously at the moment a virtual trajectory enters an advice region, and from the entering location. The flow is taken from the ex-post traffic state estimation.

As drivers are unable to perceive the maximum flow in the next 2km, advice credibility is assumed to rely on the traffic state around the driver on both the current and the target lane. Specifically, advice is assumed credible if the current speed is low or the current density is high, especially if the target lane has higher speed or lower density. Consequently the following four indicators are used: “c) current density”, “d) density difference with target lane”, “e) current speed” and “f) speed difference with target lane”. Both indicators d) and f) are calculated as $y_{tar} - y_{cur}$.
\( y_{\text{tar}} \), where \( y_{\text{tar}} \) is the density or speed on the target lane and \( y_{\text{cur}} \) is the density or speed on the current lane. Thus positive values advice a lane change towards a lane with higher speed or density.

Lane change advice may or may not be given in correlation with the lane-drop. Clearly drivers may find lane change advice credible if they can link the advice with the lane-drop, for which the distance to the lane drop is assumed important. This aspect of advice credibility is however not evaluated for lane change advice, as this advice can also be given elsewhere and may have nothing to do with the lane drop. However, the credibility of synchronize and yield advice perfectly represents the cases in which lane change advice is given in relation to the lane-drop, as the distribution advice principle will then also give synchronize and yield advice in exactly the same region (to those drivers that will not receive lane change advice).

**Keep lane advice**
Advice validity is equal to the ‘change lane’ validity. Advice credibility is equal to the ‘change lane’ credibility. Both for reasons discussed earlier.

**Synchronize advice**
Advice validity is equal to the ‘change lane’ validity. Advice credibility concerns the perspective of the driver. For this we need to make assumptions about what is, and what is not credible to users. For synchronize advice it is assumed that the distance to the lane drop (the only infrastructural change leading to these advices in the used network) is important, as drivers may understand the reason for the advice if the lane drop is near. It is difficult to state what is near at this point, but the system defines infrastructural areas with lengths of 2km. Thus, preferably distances should not be much larger than this. For synchronize advice indicator “g) distance to lane drop” is used to indicate advice credibility.

**Yield advice**
This is similar to advice validity and credibility of synchronize advice. In this case indicator “h) distance to lane drop” is used to indicate advice credibility. Note that indicators g) and h) are technically equal, but g) is evaluated if synchronize advice is encountered while h) is evaluated when yield advice is encountered. Consequently they describe the validity of the two advice categories independently.

**Short headway advice**
Short headway advice (from the acceleration advice principle) is only valid if indeed the end of congestion is within a reasonable distance downstream. In other cases, there apparently is no end of congestion to give this advice for. Short headway advice is given from 0.5km upstream until 1.5km downstream of the estimated location of the end of congestion, for which a flip-over speed of 60km/h is used. However, this assumes backward propagating congestion, which does not hold for standing congestion for instance at an onramp (which is one of the reasons why the advice is given in an area around this location). Consequently, a distance up to 2km is reasonable. Short headway validity is indicated with indicator “b) distance to end of congestion”. This is derived instantaneously at the moment a virtual trajectory enters an advice region, and from the entering location. The location of the end of congestion is derived from the ex-post traffic state estimation using a flip-over speed of 60km/h as well. If no downstream congestion is found, the distance is infinite.
Indicator b) is also appropriate for headway advice credibility, as a driver would expect such advice only near the end of congestion. A second indicator is “i) current speed”, which in itself is an indicator of whether the driver is in congestion or not. It may be assumed that if drivers are still in free flow, this advice is experienced as not credible. This situation may however occur in case of short congestion for which the driver has yet to decelerate, while the end of congestion is also already near. In other cases, a high speed indicates an error in the traffic state estimation. Note that these problems can easily be solved with in-car filtering by not giving the advice at high speeds, but in the current analysis it is interesting to evaluate how often this occurs. Finally, it is expected that if drivers are notified about the end of congestion, while they will enter other congestion quickly thereafter, this brings about some annoyance which lowers the advice credibility. In fact, for this reason these advices are not given if congestion is estimated within 2km downstream of the end of congestion. To this end, indicator “j) time until next slowdown” is used. This is derived from the virtual trajectory itself. Up to four phases are considered:

- Phase 1: The driver receives the advice while driving >60km/h. This can occur if the congestion is short and the driver has yet to decelerate for the congestion for which the advice is given. If the speed is <60km/h, this phase is skipped.
- Phase 2: The speed is <60km/h, in congestion for which the advice is given.
- Phase 3: The speed is >80km/h, the driver is in free flow.
- Phase 4: The speed is <60km/h, the driver is again in congestion.

The start of phase four is used as ‘next slowdown’. If there is no phase four, i.e. no next congestion, the value is infinite. The threshold values of 60km/h and 80km/h are assumed to coincide with drivers’ perception of congestion and free flow.

**Speed advice**

Advice validity is equal to the ‘change lane’ validity. For advice credibility it is assumed that drivers would consider speed advice credible if the advice is to a slightly lower speed if they are in traffic near the critical density (which they would call busy traffic). Some drivers may already show this behavior if they perceive busy traffic ahead, a behavior which this advice may enhance, especially if the driver is not able to evaluate the traffic state ahead due to visual blocking. Reversely, advice to a slightly higher speed is only credible if the density is low. To evaluate the combination of density and the speed difference between the current speed and the advised speed, two indicators will be used: “k) current density” and “l) speed difference with advice”. The latter is calculated as $v_{adv} - v_{cur}$, where $v_{adv}$ is the advised speed and $v_{cur}$ is the current speed. Thus positive values advice a higher speed.

Summarizing, the methodology gives the following indicators for advice validity and credibility:

- Temporal distribution of (net) advices, separated per lane and travel time.
- Spatial distribution of (gross) advices, separated per lane.
- Indicators a) through l).
RESULTS
This chapter will elaborate on the results of the log analysis by presenting the temporal and spatial distribution, as well as the situational indicators a) through l) of advice validity and advice credibility.

Temporal distribution of advices and number of advices per vehicle
In figure 7 the average number of advices of different types throughout the day (as an average of the full analysis period) is presented, together with the average travel time. A clear evening peak can be seen from the travel time, though the morning peak is much less evident. The drop in travel time at 20h is due to missing data caused by an error in the logging system, which occurs on every day at 20h when log files were sent. Generally, the travel time is strongly correlated to the number of advices that is given, especially regarding the short headway advices. Other advices are also given before congestion occurs. This is as expected as the short headway advices are given at the end of congestion while the remaining advices originate from the distribution advice principle which aims to prevent congestion.

There are also lane specific observations. The left lane predominantly has synchronization advices. The middle lane has many lane change advices, but also yield, short headway and some speed advices. The right lane mainly has keep lane and short headway advices. All of this complies with expectations from the advice principles as the left lane is dropped (therefore little short headway advices) and as the middle lane is the busiest.

From figure 7 it can also be seen that the average number of advices per vehicle is quite low, with the highest expected number of advices in the evening peak being about 2 on a 10km stretch. The low number of advices per vehicle is confirmed by table 2, where it can be seen that only few vehicles experience more than 3 (net) advices, and no vehicles experiences more than 6 (net) advices over the entire two week period. Furthermore, table 2 shows the importance of in-car filtering as the number of encountered advices is strongly reduced between the gross and the net counts. In fact, the simple in-car filter implemented in this paper is able to merge about 3 advices into 1, except for the first advice. For example, the 75 trajectories with 7 gross advices have an average of 3.09 net advices, see the 4th column. Only for $n_{gross} = 10$ this is not true, but this is due to the fact that only two trajectories had 10 gross advices.
FIGURE 7 Average number of net advices given on the left (a), middle (b) and right (c) lane over the full two week period, per time-of-day. The average travel time is also included.
TABLE 2  Number of gross and net advices encountered.

<table>
<thead>
<tr>
<th>Number of advices (n)</th>
<th>Trajectories with n gross advices</th>
<th>Trajectories with n net advices</th>
<th>Average number of net advices for n gross advices</th>
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<td>0</td>
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<td>0</td>
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</table>

Spatial distribution of advices
The temporal distribution of advices shows that the differences between lanes are as expected given the advice principles. The spatial distribution of different advices is presented in figure 8. As to the differences between lanes this is equal as in figure 7, the temporal distribution. There are however some additional observations to be made concerning the longitudinal (i.e. driving direction) distribution. Short headway advices are almost all given between the lane drop and the next off ramp. This is in accordance with the known sources of congestion which are spillback from the off ramp and the lane-drop with a busy onramp [4]. Furthermore, lane change advices are usually accompanied by a lane keep advice and by yield advices for about 33% and synchronize advices for about 40%. This strongly depends on whether the trigger for distribution advices is upstream or downstream of the lane-drop, as yield and synchronize advices are only given upstream of the lane-drop. Remaining differences can be explained by the overlap filter (step 3 of the advice algorithm). The spatial distribution of advices is thus in accordance with expectations from the advice principles, which indicates advice validity.

FIGURE 8  Spatial distribution of advices of the full two week period.
Indicators for advice validity and credibility

The advice validity and credibility indicators of different advice categories will now be discussed.

Change lane and keep lane advice

Validity and credibility of advices from the distribution advice principle, including synchronize, yield and speed advice, is derived from the indicators presented in figure 9.

![Figure 9: Indicators for distribution advice.](image)

The maximum flow within 2km is higher than 2000 veh/h, the trigger value for distribution advices, for only 25.8% of lane change advices. This indicates that advices from the distribution advice principle are often not valid. This is also in line with speed advices often being given at low densities (presented further down). Since lane change advices are usually given from the middle to the right lane, it is not surprising that the target lane has densities which are usually 0 to 12 veh/km lower than in the current lane. Similarly, it is not surprising that speeds on the target lane are 0 to 25km/h lower, because of trucks. Concerning advice credibility, the lower density is favorable but the lower speed is not. Most lane change advices are given for densities below 25 veh/h and speeds above 80km/h, which is as intended as lane changes are advised to prevent congestion. Summarizing, advices from the distribution advice principle have limited validity. Lane change and lane keep advice also have limited credibility due to the lower speeds on the target lane.

Synchronize and yield advice

In figure 10, the distance towards the lane drop for synchronize and yield advices is shown. These are in the range between 1 and 4 kilometers upstream of the lane drop. The larger distances may be rather early for some drivers, possibly delaying the moment when drivers become compliant. However, they do allow sufficient time to perform smooth merging. Advice credibility may not be optimal for all synchronize and yield advices.

Advice validity for synchronize and yield advice is equal to lane change and lane keep advice, as these stem from the distribution advice principle.
FIGURE 10  Indicators for synchronize and yield advice.

Short headway advice
Figure 11 shows the indicators that are concerned with short headway advices. For 16.7% of these advices, no congestion is encountered from which to accelerate (hence the cumulative probability of indicator b) up to 0.833). This can be (partially) explained by the delay in the detector data which causes the algorithm to assume congestion for about 3 minutes after it actually has been solved, including very small breakdowns that are quickly solved. Note however that short headway advices can be filtered in-car as they should only be given if the vehicle has a speed below e.g. 80km/h. For 6.4%, the advice is given while the end of congestion is more than 2km downstream.. The majority of the remaining advices is given between 0.7km and 1.7km upstream of the end of congestion, which is reasonable as drivers need some time to become more active.

For 19.2% of short headway advices the speed of the vehicle when the advice is first given is above 80km/h, which can be (partially) explained by the lack of actual congestion. For 16.9% the speed is between 60km/h and 80km/h, whereas congestion is recognized below 60km/h. This may be partially due to short congestion for which the driver is decelerating when the short headway advice is first given. In fact closer examination of the trajectories reveals that 39.2% of drivers that get short headway advice while driving above 60km/h do find the end of congestion within 2km. For speeds above 60km/h but below 80km/h this is 58.0%. Some of these drivers might not encounter congestion at all. Of the drivers that do encounter congestion, 71.3% experience the end of the congestion within 2km. For speeds above 60km/h but below 80km/h this is 79.7%.. For the remaining 63.8% of all drivers the speed indicates that the driver is in congestion when receiving short headway advice.

Finally, the time until next slowdown shows that in practically all cases (indicator j) lies just above the x-axis, but too little to be visible) there is no next slowdown, i.e. drivers do not have to slow down shortly after receiving the advice to maintain a short headway while accelerating out of congestion. However, there may be drops in speed before 80km/h is reached, which drivers may consider ‘new’ congestion.

Closer examination of the trajectories, starting from the moment that short headway advice was given, reveals that indeed such drops in speed are present. Between the moment that
the minimum speed during advice is reached, and the moment that 80km/h is reached, for instance 21.3% experience a drop of 5km/h or larger. The percentage decreases to 10.3% for a drop of 10km/h or larger, and 2.2% for a drop of 20km/h or larger. It is however unknown what drop in speed may be considered as new congestion, and the absolute speed from which the drop starts may also be important.

Overall, short headway advices are valid and credible, though credibility may be improved by obtaining a better understanding of what drivers consider a drop in speed which is conflicting with such advice. Furthermore, for 36.2% the speed when receiving this advice indicates that deceleration for short congestion is first applied, after which drivers indeed encounter the end of congestion. Although the end of congestion is indeed near in 71.3% of these cases, advice may be less credible if drivers are still approaching the congestion.

FIGURE 11 Indicators for short headway advice.

**Speed advice**

Figure 12 shows the indicators for speed advice. The cumulative distribution (figure 12a) shows that the current density is usually below 20 veh/km when speed advice is given. This is expected as the advice is intended to be given in free flow. However, speed advice should only be given in near critical traffic, while clearly this advice is often given in low density traffic. This discrepancy was further discussed with the advice validity of lane change and keep advice (i.e. the distribution advice principle). The advised speed is higher than the current speed for 28.3% of the advices. Here, the traffic state estimation makes an error as speed advice should only be given if the current speed in a section is larger than the target speed.

Speed advice is assumed credible if a slightly lower speed is advised at a density near the critical density. Or, to a higher speed in low density. This can only be evaluated with a combination of both indicators, which is shown in figure 7.10b. It shows the opposite of what is assumed credible; lower speeds are advised at lower densities. The cause of this may be the fundamental relation between density and speed, i.e. at lower densities the speed is higher and consequently a lower advised speed is further from the current speed. Summarizing, speed advice seems not credible. This may be partially explained by the advice not being valid (i.e. being given in unintended circumstances), which is evaluated for lane change and keep advice.
FIGURE 12  Indicators for speed advice.

DISCUSSION AND CONCLUSIONS
The empirical results show that the advisory system generally operates as expected. Advices of different types have a spatial and temporal distribution which is in accordance with the used advice principles. Advices from the distribution advice principle however have limited validity with 25.8%. This is probably an important cause of the little effectiveness of lane change advices that was found in earlier research [4], besides negative side effects that have to do with increased flow on the right lane causing more interference with a busy onramp and off ramp with spillback. These advices were intended to advise drivers to change from the busy middle lane in case of high inflow. It however appears that flow is fluctuating to such an extent, that giving such advices upstream of a trigger results in giving advices in areas where the flow can be considerably lower, as shown by indicator a) in figure 9. Besides the lane change advice, this also explains the low validity of speed advice. Therefore it is probably better to give lane change advices around the trigger, though this is less anticipatory then originally intended.

Considering human factors, advice around the trigger may be less desirable concerning safety as triggers are more likely in high driver workload circumstances. In [17] and [18] it is found that workload is higher for more complex and busier traffic, where triggers are more
likely. More research into the human factors of in-car advice is required.

The data delay and coarseness (1 minute aggregation) may contribute to mismatches between distribution advice triggers and actual flow, since critical platoons that exist due to the lane drop, may become non-critical if only a few vehicles move from the platoon to another lane. With a delay of 2-3 minutes there is sufficient time for this to occur. More detailed and less delayed detector data, or possibly full trajectory data using cameras at critical locations, may allow for a significant improvement regarding the validity of lane change advices.

Advice frequency is reasonable, as on average only up to 2 advices are given on a 10km stretch during evening peaks. It is important to have a robust in-car filtering and merging of advices, to avoid double but equal advices which significantly increase the number of given advices, and to avoid advices from being given when they are only active for little remaining time or distance. Credibility concerning willingness to comply with advice is different between advice categories. Synchronize and yield advices are now given as early as 4km upstream of an infrastructural cause, which is a combination of a 2km section being defined as a lane-drop section (or some other infrastructural change) and a 2km section upstream of a trigger in which advices are given. Combined, this may be too long for drivers to mentally link an advice with the infrastructure. In order to allow drivers about 1 minute (i.e. 2km at 120km/h), the advice region has to stay 2km in length, but the infrastructural section length could be reduced to for example 1km. Short headway advice is credible in 76.9% of the cases (end of congestion within 2km). A large proportion of the remaining 23.1% may be easily filtered in-car by only providing this advice at speeds that indicate congestion. Furthermore, if the traffic state prediction is enhanced e.g. with floating car-data, acceleration advice credibility can be expected to improve.

To assess the willingness to comply with advice, a number of assumptions has been made concerning what drivers would find a credible circumstance for the advice. The analysis shows that this aspect of advice credibility is not always present. This is however to be expected as the basic principle of advice on the tactical scale is that drivers have an opportunity to perform maneuvers concerning a (potential) problem which is about 1-2km downstream and which drivers cannot yet perceive. The circumstance in which drivers get advice is thus structurally different from the circumstance for which the advice is given. To enhance advice credibility, a motivation for the advice may also be provided to the driver. A possible downside of this could be an increase in workload and the net effect could be an interesting topic for future research.

Finally, it should be mentioned that the short headway advices are robust with respect to advice validity, advice credibility and effectiveness (see [4]). Therefore, these advices alone show the strong potential of in-car advice on a tactical scale.

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