Bavarian Road Administration uses Probe Data for Large-Scale Traffic Signal Evaluation Support

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Abstract

The Bavarian Road Administration (BRA) is responsible for all extra-urban traffic signals in the German state of Bavaria. The BRA is instructed by ministerial decree to establish a quality management system for its traffic signals including periodical reviews of relevant performance indicators at the signals. Proposed practice is to interview the participating 19 State Building Offices. However, such an approach would be expensive, time-consuming and not sufficiently consistent.

The paper presents an alternative multi-step approach to support the required signal reviews in a large-scale generic analysis. The procedure is solely based on anonymized GPS probe data from navigation devices and works in the following way: a special fine-granular digital map together with the locations of the traffic signals work as starting points. Then, in a generic geo-fencing step the areas of influence around the signalized junctions are determined and the probe data is map-matched onto that qualified network. From this map-matched data paths are identified that represent the different maneuvers of the probe vehicles through the intersection area. Finally, delay times and other indicators of all the travelled paths at a junction are calculated by comparing all individual measured path travel times with reference travel times on the paths. These reference travel times have also been calculated from GPS probe data analyzing path-speed distributions.

This is the first time an approach was developed which allows an automatic analysis of a huge number of traffic light control systems at intersections at a time. It was possible to provide the data and figures of 2300 Bavarian traffic signals to the BRA in support of the evaluation of their traffic signals.
INTRODUCTION

The Bavarian Road Administration (BRA) manages more than 2300 traffic light systems in the interurban road network of the German state of Bavaria. They are spread all over the state, with most of them located at major rural intersections or at peripheral stretches of main urban roads and access routes.

The poor control of traffic signals at intersections often creates traffic bottlenecks, especially along typical commuter routes. With an increasing number of vehicles passing a traffic light every day, most of the traffic jams occur during peak hours. In addressing this challenge, the BRA has instructed its Central Division for Traffic Management (CTM) to establish a quality management system for the traffic lights under their responsibility. It should be based on the German technical standard “Guidelines for Traffic Signals” (GTS, [1]), published by the Road and Transportation Research Association (RTRA), which gives recommendations for setting up processes. According to this regulation, each traffic light controlled junction should be periodically reviewed with respect to relevant performance changes and traffic flow at the junction, as well as to traffic light malfunctions and errors. The performance of each junction should be mapped to a quality level. If the quality level of a signalized intersection turns out to be insufficient, reasons should be identified and an action list proposed to improve the performance. After assessing potential improvements, one or more actions need to be realized.

A very challenging first step is to get an overview about all traffic lights and to rank their performance, to identify those traffic light systems which are especially critical with respect to delay. Almost no data is available to the authorities, such as time-dependent queue length, traffic flows or travel times. To have no conventional traffic data collection infrastructure in place is a common situation for non-urban signalized junctions. In recognition of this fact the GTS recommends interviews with the responsible technical officers in the 19 State Building Offices. Clearly, this cannot be considered as an objective approach, especially if the aim is to get a consistent view of the situation. Therefore, the CTM has been looking into data driven technical approaches without investing in extra monitoring equipment. The administration has finally decided to use existing anonymous records of Floating Car Data (FCD). In contrast to technologies like Bluetooth or systems for automatic vehicle identification which may provide higher sample rates, this solution is free of any extra infrastructure investment. In cooperation with TomTom’s Department of Traffic & Travel Information, a delay-based methodology has been developed, primarily focused on the specific task to extract additional information to pinpoint the vehicular traffic quality of signalized intersections in the non-urban network of Bavaria.

Although FCD can certainly provide fundamental insights of vehicular traffic at junctions, it’s important to note that complementary data and investigations are required for a comprehensive junction performance analysis. In particular, other modes of transport need to be considered, intentional “non-optimal” traffic light control may have an impact, e.g. due to public transport prioritization etc. Furthermore, the developed methodology primarily focuses on isolated intersections, since the evaluation of traffic signal coordination along a route may require different data processing.
GPS Probe Data and Traffic Signals

The usage of vehicle probe data in the context of signalized intersections has been subject to broad research. Contributions range from monitoring, controlling to optimizing signals both in an off-line and in an on-line manner.

A valuable introduction into the topic is provided by van Zuylen, Zheng and Chen in [2]. They explain different aspects of using ‘Probe Vehicle Data’ to derive information on the traffic state including travel times along signalized arterials.

In [3] Oertel et al. describe a method to use measured vehicle delay times to control traffic signals at an isolated intersection in real-time. The approach is tested with micro-simulation.

Meijer et al. illustrate in [4] a procedure to determine delay and turning movements at intersections using GPS probe data. They evaluate their method by comparing the results to an analysis gained on the basis of loop detector data for two selected junctions in the Dutch city of Delft. Interestingly, the authors use local speed limits as well as measured speeds to derive reference travel times which are needed to calculate delay times.

Another contribution to this topic is [5] by Chunmei et al. They focus on the estimation of several signal parameters like the phases, ‘status-change times’ or ‘green time beginnings’. In experiments they prove the efficiency and reliability of their approach.

Ban et al. [6] introduce an algorithm to estimate arterial signalized intersection delay patterns. As an evaluation of their method they conduct a field study including a single junction.

Hanabusa et al. [7] estimate delays at adaptively controlled signals in real-time. They compare the results gained from ‘probe data’ and ‘automatic vehicle identifier’-techniques. However, all delay figures are validated in simulation tools only.

Also Nagashima, Hattori and Kobayashi use micro-simulation as evaluation method. In [8] they aim at reducing CO2 emissions by introducing a control system that more accurately calculates queue lengths at the approaches of an intersection.

Several contributions to research on queues at signalized junctions were made by Neumann, [9], [10] and [11]. For example, in [11] Neumann describes queue length changes over the day, which are detectable even with a low penetration of floating cars. He compares his results to ground-truth queues given from simulations.

Comert and Cetin focus on real-time queue length estimation using probe data at an isolated intersection, [12]. Like Neumann, they investigate the accuracy sensitivity with respect to the probe density. Furthermore, in [13] they evaluate queue length estimation errors with analytical models.

Also Ban et al. estimate queue lengths in real-time, [14]. They discover that queue length or signal timing changes can be deduced from critical patterns in intersection travel times. For the evaluation a field experiment and simulations are conducted.

Two recent contributions come from Unal and Cetin, and Cetin and Rakha. In [15] Unal and Cetin address the estimation of queue dynamics and delays at signalized intersections. In tests with data from a micro-simulation they show that their approach applies to signals in both under- and oversaturated condition. In [16] Cetin and Rakha use probe vehicle data to estimate fuel consumption and CO2 emissions at a signalized intersection. They applied their approach to simulated data.

In [17] Hunter et al. use probe vehicle data to conduct a before-and-after study regarding the installation of a new adaptive signal controlling. They focus on the analysis of typical
operational performance indicators. The test site includes 15 signalized intersections in Cobb County, GA.

Despite this rather large body of literature, there is to the best of our knowledge no literature available on addressing the problem of an automatic pre-selection of potentially poor-performing traffic light control systems in a large scale manner as outlined in this paper.

**THE BAVARIA CASE STUDY**

The case study in Bavaria includes a set of approximately 2300 signalized intersections which are quite uniformly spread over the whole state of Bavaria. All the signals are located in small municipalities and along federal roads. Traffic signals in greater urban areas like the cities of Munich or Nuremberg are not subject of this study.

The traffic signals do not have a unique type. Most of the considered signals are fixed-time controlled but the list also includes adaptive signals, those with a public transport prioritization, few with green wave coordination and even some pedestrian signals.

**FIGURE 1** Approximately 2300 signalized junctions from all parts of Bavaria have been evaluated.
The time period chosen for this analysis is the year 2012. On the one hand, it is important to have sufficient volumes of probe data available for the analysis. On the other hand, too large time spans have the disadvantage that structural, traffic-related and signal specific changes may have occurred which may be very hard to detect and filter. Also, by taking a complete year for the analysis, seasonal effects are minimized.

The goal of the Bavaria case study is to evaluate all the traffic signals at once but as individual signals. Groups of signals that are coordinated should finally be evaluated as whole groups. Currently, they are evaluated individually. This has to be taken care of in the post-processing, i.e., in the actual signal adaptation step.

As a result, the study shall provide a list or ranking of the 60 worst signals, which refers to those signals with a preferably obvious sub-optimal signalization. This ranking shall be understood as a recommendation for an in-depth investigation. It is important to understand that the study does not aim at suggesting optimized signal controlling.

All the relevant data like coordinates of the signals, names, types etc. were collected and provided by the Bavarian Road Administration.

**TRAFFIC SIGNAL EVALUATION WITH GPS PROBE DATA**

An automated algorithm has been developed, which takes a set of data as input and automatically computes a set of quality indicators, meta-data and visualizations per intersection.

First, a digital road network map covering the State of Bavaria has been conditioned and compiled to allow for a consistent and high-resolution travel time analysis. Second, anonymous TomTom probe data from navigation applications has been map-matched to the digital road network of the state of Bavaria. During the map-matching procedure, road element related travel times have been calculated, forming a database of travel time measurements. A network analyzer, taking the locations of the intersections of interest as input data, automatically assembles those parts of the network in the vicinity of a junction which needs to be evaluated to understand the traffic behavior. Possible turning movements are determined out of the data, and a reference state per allowed turning maneuver is constructed by exploiting the modes of the travel time distribution along a path. Performance measures per path and junction are calculated, first by analyzing the delay times per traversal, and finally by aggregating data from all traversals.

The details of the developed methods are described in the following paragraphs. The approach to evaluate the signalized junctions is divided into several steps all of which will be explained below:

1. Map preparation and map-matching
2. Geo-fencing
3. Junction path determination
4. Reference travel times or free-flow speed determination
5. Calculation of key performance indices (analysis)

**Map Preparation and Map-matching**

For the study, a special digital map was used that is based on the TomTom MultiNet map ([18]) for Germany, in version 2013.01. This map contains the detailed layout of the street network as well as a plurality of additional attributes, like the *Functional Road Class* (FRC) or the *Form of Way* (FOW) for a link.

The main characteristic of the special map is that it is compiled in such a way that its links have a maximum length of 50m. This is essential to get a network with a sufficiently high
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geometrical resolution around the signalized junctions. In addition, the geo-fencing, which is explained in the next section, is much more effective on such a spatially fine-granular network.

In a next step TomTom GPS probe data is map-matched onto the digital map. This FCD is fully anonymized and comes from TomTom navigation devices as well as from cell phone apps. All data was collected with user consent. FCD from commercial fleets is not included. Hence, it is reasonable to assume that most of the data used is from GPS probes from passenger cars. Comparing the TomTom probe flow with available loop data shows shares of roughly 1% – 1.5% but it may vary from intersection to intersection.

A single TomTom GPS probe record (a trace) contains a 24-hours portion of positioning data of a single vehicle. For privacy reasons it is not only anonymized but also slightly truncated. The positioning data include latitude, longitude coordinates and according time-stamps in a certain time interval. The length of this recording interval is usually 1 to 5 seconds.

In the map-matching process the FCD is now referenced to the digital map. This is done trace by trace. The procedure works as follows: consecutively, for the positions nearby links from the digital map are determined. Then, between the links of consecutive positions the most probably route is calculated taking into account the positions time stamps. Then, one can easily derive speed values for the single links on the calculated route using the coordinates, which are projected onto the route, and the time deltas. This process gives a universe of derived speed data which is stored in a geo-database. At the end of the map-matching, this geo-database contains link-based speeds together with time stamps indicating the ingress time into a link and some other meta-data. This database is the basis of the analysis of the signalized junctions.

Geo-fencing

For the analysis of a single signalized intersection it is essential to define a relevant part of the street network around the junction representing the area of influence of the signalization. This is done in three consecutive steps. First, we consider all links of the network that start or end inside a circle within a radius of 100m around the signal's center-point. Extensive preliminary investigations yielded this value since it is a good compromise to sufficiently cover signal related effects like queues and to not capture signal-remote traffic effects. All links that are not contained in such a circle are not considered for the analysis.

In the second step, the circle is cleaned up from all the links that don't interfere with the signalized junction. For example, the map attribute FRC can be used to filter links on a highway which may be close to an intersection nearby the highway's off-ramp. In the same way not-navigable links are discarded. In the end, this means filtering out links with FRC values equal to 0 or greater than or equal to 8 as well as links with a ONEWAY map attribute value of N which is for prohibited for motorized individual traffic. Finally, for the second step, the attribute FOW is used to filter links that belong to parking lots.

Ultimately, in a third step, two position dependent filters are applied. First, links are filtered if their end point is outside the 100m circle and their start point is not directly nearby the center point of the signal. In addition, all links are filtered that fulfill certain conditions on their orientation (directed away from the center point). Both steps eliminate downstream links that are not relevant for the analysis.

All the links within a signal's circle that are not filtered out are used for the signalization evaluation.
Finally, it is important to mention that the geo-fencing has to take place after the map-matching, since the most realistic network possible is required for the map-matching, because trajectories of FCD may not be representable on a thinned out map.

**Junction Paths**

As mentioned before, the evaluation of the signalized intersections is based on analyzing map-matched GPS probe data. This data is map-matched to street segments (links) of a digital map. However, the analysis is not done on a link basis but rather on paths through the junction. It is not possible to calculate realistic free-flow travel times on the basis of data analyses for the individual links because they strongly depend on the vehicle maneuver at the intersection. Hence, the analysis is done on the paths (full turn maneuvers through the intersection) of the vehicles.

Also the determination of the junction paths is done in an automated process. However, defining the paths depending on the network layout in a process similar to the one applied for the geo-fencing is difficult. Hence, the GPS probe data, or the map-matched data in the geo-database, respectively, is used to define the paths. Therefore, all map-matched data for all links in the circle around the signal, which have not been filtered in the geo-fencing step, is read. Then, all the single traces are reconstructed, which is done via a random id that was given to the data during the map-matching. During the reconstruction, series of link data points which are chronologically sorted are created. Note that this way one can derive a travel time for the series, i.e., the trajectory of a vehicle through the intersection canonically from the single link data points.

However, depending on the characteristics of the network around the junction, e.g. possibilities for on-street parking and on data artifacts like turned on or turned off GPS devices during the path traversal, the method described above can create partial paths. These partial paths may not constitute full traversals through the junction via the signal. Therefore, they should be filtered out. This filtering is done using a simple path coverage condition. Namely, all paths are discarded and not used for the analysis when they have less than 500 traversals. Another reason to filter paths with few data is that it is difficult to derive a realistic reference travel time for them. Typically, by applying this filter only 10% to 15% of data remain unconsidered.

It has to be noted that the path determination has to happen on the thinned out street network. Otherwise, the method would lead to too many degenerated paths, e.g. including supermarket gateways.

**Reference Travel Times**

The determination of a reference travel time for a junction path or a reference speed, respectively, is essential for a realistic estimation of delay times. If the reference travel time is set too high, e.g. by considering the fastest traversals of a path, this will lead to an unrealistic high delay time that is not representative. On the other hand, with a low reference travel time, for example the median of all measured values, weaknesses of the signal may not be detectable.

A possible approach to determine a reference or free-flow speed on a path could be to take a high speed percentile, e.g., the 60th or 70th percentile. However, a disadvantage would be that such a speed value is not always representative for the traffic in its free-flow state on the path. Rather, it could deviate a lot from the most likely speeds in an unimpeded state. Other ways
to get a reference speed such as considering traversals during night hours also deliver problematic results.

For our signal evaluation we decided to take typical path travel times of vehicles that pass the signal at green phases as reference. This definition should also coincide to the state where vehicles pass an inactive signal without being impeded by other vehicles. Since some traffic signals are indeed inactive during night hours this is a consistent estimate for all signals.

![Histogram of single path speed measurements](image)

**FIGURE 2** Speed histogram of a junction path: Two modes of the distribution can clearly be observed. The 60th speed percentile has a value of approximately 29 km/h. The free-flow speed is set to the value that corresponds to the mode of the highest speed, 48 km/h in this case.

Hence, the determination of a reference speed on a path requires the identification of the mode of the speed distribution that belongs to the travel time of a vehicle during an unimpeded green-phase of the signal. For the speed distribution on a path all single observations are used including those on weekends and night hours. Then, the reference or free-flow speed is set to the speed above the 60th percentile speed with the highest frequency. The 90th percentile speed is taken as an upper bound. See FIGURE 2 for an example speed distribution and the according free-flow speed determination.

To avoid influences from artifacts in the data and, hence, in the reference speed determination, the speed histogram (red curve in FIGURE 2) is slightly smoothed. In rare cases this smoothing may lead to merged or even eliminated modes. However, these effects are in general insignificant for the reference speed calculation.

Ultimately, the free-flow travel-time can be calculated easily from the free-flow speed.
The Key Performance Indicators (KPIs)

In this section the performance indicators for a signalized intersection will be explained. This includes indicators for the single paths at an intersection. All indicators have in common that they are computable from FCD of medium size volumes.

Some formal notation will help defining the path-based as well as the signal-based performance indicators: Let $P$ be the set of paths at a signalized intersection and $p \in P$ a single path. The number of traversals of a path $p$ is indicated with $n_p$. Furthermore, let $tt_{ff}^p$ be the free-flow travel time of a path $p$. A single measured travel time of a path $p \in P$ will be denoted by $tt_i^p$ where the index $i$ runs between 1 and $n_p$.

Path-based KPIs

The total sample delay $d(p)$ on a path $p \in P$ is defined as the sum over all single measurements of the difference between the measured travel time and the free-flow travel time, i.e.

$$d(p) := \sum_{i=1}^{n_p} (tt_i^p - tt_{ff}^p).$$

Then, the delay per vehicle $dpv(p)$ is the total sample delay normalized with the total amount of measurements. Hence,

$$dpv(p) := \frac{d(p)}{n_p}.$$

Finally, the travel time index $tti(p)$ is defined as the ratio of the sum of all observed travel times at the path and the total travel time that would have accumulated if the vehicles could have passed the path at free-flow speed. Formally,

$$tti(p) := \frac{\sum_{i=1}^{n_p} tt_i^p}{n_p tt_{ff}^p}.$$

Signal-based KPIs

Now, canonically, signal-based KPIs can be derived from the path-based ones. First, the total sample delay $ds$ at a signal is defined as the sum over all total sample delays of the signal's paths:

$$ds := \sum_{p \in P} d(p).$$

Moreover, the delay per vehicle at a signal is given by the total sample delay over all paths divided by the total number of path measurements,

$$\frac{ds}{\sum_{p \in P} n_p}.$$

Finally, again, a travel time index can be computed:

$$\frac{\sum_{p \in P} \sum_{i=1}^{n_p} tt_i^p}{\sum_{p \in P} n_p tt_{ff}^p}.$$
In addition to the above mentioned performance indicators other measures were under investigation, including e.g. the total sampled number of standstills for a path and the average duration of such a standstill. However, these indicators are not based on map-matched data, but rather on raw GPS data. Therefore, the methodology is based on a different processing chain. Also, it has to be mentioned that deriving stop related performance indicators requires more fine-granular source data; only GPS probes with a sample interval of 1s can be used to calculate these additional KPIs. Because of these reasons it was decided not to include other performance measures for this study than the ones previously described.

### Evaluation Results

The sections above described the steps 1 to 4 of the method for the signal evaluation. The actual analysis (step 5) is finally done in a straightforward iteration over all signals and all paths of a signal where all path travel times are considered and values for the indicators are calculated.

Outcome of the analysis are fully evaluated signals for the year 2012. As the relevant performance indicator the \textit{delay per vehicle} is used for the ranking. This KPI is close to what the GTS ([1]) uses in their quality management. In addition it is a good compromise between the \textit{total sample delay} with the risk of accumulating many small delays to a misleading high value and the \textit{travel time index}, which is not that intuitive to interpret and cannot be easily compared to standard performance indicators.

To ensure to catch only the important signals, i.e., such where concrete signalization changes would have the highest effect, one can additionally filter low coverage signals from the ranking. In the Bavaria study, signals with less than 10,000 samples in 2012 are filtered out. Here, samples refer to the total number of sampled traversals on all paths of the junction. More than 70% of the signals from the study fulfill the criteria.

<table>
<thead>
<tr>
<th>Junction location</th>
<th>Delay per veh [s]</th>
<th>Total Sample Delay [h]</th>
<th>Travel-Time-Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weilheim, Münchener Str.</td>
<td>29.9</td>
<td>113.77</td>
<td>2.273</td>
</tr>
<tr>
<td>Landshut, B15</td>
<td>27.4</td>
<td>281.26</td>
<td>2.307</td>
</tr>
<tr>
<td>Deggendorf</td>
<td>22.9</td>
<td>118.23</td>
<td>1.748</td>
</tr>
<tr>
<td>Wilhermsdorf, FU18</td>
<td>15.3</td>
<td>85.47</td>
<td>2.247</td>
</tr>
<tr>
<td>Near Hohenlinden, B12</td>
<td>9.0</td>
<td>233.53</td>
<td>1.625</td>
</tr>
</tbody>
</table>

Table 1 shows the results for a few selected signalized intersections with different delay per path-traversal values. While the intersection in Weilheim with its 29.9 seconds delay is among the Top 5 of the ranking, vehicles at the junction near Hohenlinden experience on average a relatively low delay. However, the total sample delay suggests a higher significance of the latter one. Similarly, the indicators \textit{delay per vehicle} and \textit{travel time index} for the junctions in Deggendorf and Wilhermsdorf are complementing each other by providing different views on the performance. On average, vehicles in Deggendorf witness larger delays than vehicles at the junction in Wilhermsdorf. At the same time, the optimization potential in Wilhermsdorf may be larger since the \textit{travel time index} is higher. Also, this constellation could indicate that free-flow speeds are higher in Deggendorf than in Wilhermsdorf.
Hence, this example shows that only by taking all the performance indicators into account, a comprehensive view of the signalization at the junction is given.

In summary, among the analyzed intersections about 60 hotspots with insufficient performance were identified. The first 15 junctions of the ranking were selected for an on-site investigation. The BRA mandated a traffic engineering company to perform further analyses. The focus was on the evaluation of the results by exploiting additional data and on-site inspection. The investigation confirmed that in all cases these findings correspond to delay time / loss time and assigned quality index / KPI. After finalizing the on-site inspection, the results will be documented to support BRA.

**Detailed Results**

In addition to the evaluation of the signals as a whole, the analysis also provides results on the single paths of a signal. These detailed results may have an immense additional value since they give clear indications on which paths, i.e., which turning movements at the intersection, longest delay times occur.

Moreover, in such a detailed analysis for a path it is even possible to visualize all single measurements and get more insight into measured speeds at different times of the day.

![Figure 3](image)

**Figure 3** All single 7409 speed measurements for a southbound path at the junction Kufsteiner Str. in Rosenheim in 2012. The horizontal green line indicates the free-flow speed.
FIGURE 4 All single 17815 speed measurements for the left-turn maneuver at an intersection in front of the on-ramp to the A995 in the south of Munich. The measurements are grouped by day of the week. The horizontal green line shows the free-flow speed.

For example, FIGURE 4 shows a scatter plot of all single measured speeds for a selected path on a signal. The data is grouped by day of the week. Significant speed drops during peak hours on Monday to Thursday can clearly be seen. On Fridays, the evening peak speed drops are not that sharply pronounced.

In addition, the scatter plot in FIGURE 3 shows the single speed measurements chronologically over the year 2012 for a selected path on a signal. An increased coverage together with lower observed speeds can be seen during the summer months.

In general, these additional diagrams can help to detect, for example, constructions sites, blockings or lane restrictions (FIGURE 3), or changes in the signals' timing plans (FIGURE 4) at the signalized junction.

Limitations and Challenges

The proposed method for using GPS probe data to automatically evaluate a very large number of signalized junctions simultaneously can have certain limiting factors.

For some signals, the performance indicators may be influenced by construction sites at the junction or by a signal-timing plan which was changed during the year 2012. This is not eliminated from the calculation. However, the diagrams provided as detailed results indicate where post-processing is needed.
Also, it cannot be ruled out that some GPS probe data maybe be wrongly map-matched to the digital map. In rare cases this may lead to wrong speeds in the geo-database.

Moreover, the calculation of a reference speed on a junction path can be challenging in some cases, especially when no clear modes are detectable. This may lead to both, an over- or an underestimated delay. However, the diagrams help by indicating which paths are affected.

Due to the goal to provide an automated and therefore not overly complex method for the signal evaluation, the special case of nearby signals was not addressed during the geo-fencing step and the junction path determination step. In case two or more signalized junctions are close to each other they are not actually independent from each other. Rather, parts of paths from one signal may also be parts from paths of other signals. That means, delay time that is charged to one signal may actually have occurred at a different signal. Ideally, such block-signals should be analyzed together as one signal by relaxing the 100m circle radius threshold and by defining an according set of paths through the series of junctions.

Finally, evaluating signalized junctions by calculating a travel time delay for junction paths needs a reference travel time for the paths. This reference was chosen as to represent a free-flow mode on the path. It aims to model the travel time of a vehicle traversing the path unimpeded during a green phase. However, signals with paths that are almost always jammed may exist. For such paths an actual free-flow mode may not exist. Hence, the method will underestimate the actual delay on such paths.

CONCLUSION AND OUTLOOK

The identification of junction delay hot spots with applying FCD-based analysis has been proven to be a reliable method that ensures an objective evaluation of vehicular traffic conditions at an intersection over a longer time period. The developed methodology delivers detailed additional information supporting the responsible authorities to understand the interaction of traffic and signaling. With the help of the derived junction KPIs, an automatic pre-selection of junction locations with potentially poor quality has been achieved, which can be used to support further investigations and inspection in the field.

Within the quality management for traffic light systems the performance ranking of controlled intersections is definitely a major task for further activities. Next steps regarding enhancements of the evaluation method could be the following: the geo-fencing could be done adaptively. For example, bigger junctions could be automatically recognized, e.g. by a characteristic network layout and/or by additional map attributes and a larger circle for the affected area, e.g. with a radius of around 150m could be allocated.

Also, the method should be capable of handling nearby signals appropriately, i.e., (i) recognize them, (ii) apply a suited geo-fencing and, (iii) define the junction paths through the larger intersection area. However, calculating reference travel times for paths through complex intersections with several signals will be challenging since the modes in the speed histogram will be much less pronounced.

Parameterization can be better aligned with the needs of road authorities. An important quantity in this context is certainly the definition of junction reference states. Currently, this is solely based on measured data, but posted speeds or legal speeds can be incorporated.

Meta data may also improve the results. This can be information about the type of the junction, about traffic light cycle plans and their specialties. In particular, knowing exactly the
signal systems being part of a coordination or green wave allows a meaningful handling of those intersections during processing.

Finally, also adding new performance indicators should be tested. For example, queue lengths related KPIs could give more insights about the signalization quality. Also, evaluating the performance indicators for working day peak hours could be informative as to the robustness of the signalization. Vehicle stop probabilities at a junction and measured vehicle stop duration distribution are other potential KPI extensions.

Regarding the Bavarian application, the FCD-based analysis will be used in a before-after analysis as a method to review and document the outcome of an activity, e.g. a better optimization of a traffic light system. Preferably, the described approach is to be integrated and extended under the roof of a larger junction quality estimation framework.

REFERENCES


