



Automatic Incident Detection Based on Bluetooth Detection in Northern Bavaria

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Abstract

This work describes an approach to determine the current travel times on freeways based on the detection and re-identification of Bluetooth devices onboard of vehicles using stationary roadside Bluetooth detection technology. It also aims at using this information for the traffic state determination of a whole freeway network with the goal of a fast and reliable dynamic net control in incident situations. Based on a four-year experience in a Bluetooth detector test bed in Northern Bavaria, Germany, and after the evaluation of hundreds of millions of single detections, the technology as well as the developed algorithms for validation and evaluation of the data show their feasibility in practical use, especially in areas with a low density of stationary detectors like inductive loops.

The data-driven part of the approach is divided into three subsequent steps. These steps are the determination of travel times, the data filtering and validation of plausible travel times and the automatic incident detection. The determination of travel time is based on the time stamp of the detection of a Bluetooth device with the shortest estimated distance to the position of the Bluetooth detector. For the data filtering the “Time Dependent Comparison to Neighbor Values Filter” will be applied. This filter allows for a fast and reliable differentiation between unrealistic (due to stops, detours, back and return trips etc.) and plausible travel time values for a certain segment of the freeway and is based on a method to validate if the determined travel time is in a plausibility threshold corridor defined by the values of the previous and the next neighboring travel times.

The outcome is a detailed travel time information for the whole freeway network which is used for an automatic incident detection, which was developed and calibrated within this research project. This includes the detection of the start of an incident as well as the end of an incident. The result is continuous information about the prevailing travel times and a fast and reliable traffic state information for all segments, which allows for a dynamic large-scale re-routing in the Bavarian freeway network in case of congestions or other disturbances of the traffic flow.

Keywords: Automatic Incident Detection, Bluetooth, Congestion Warning, Re-Routing, Traffic State

1 Background and motivation

Traffic, transportation and mobility in general, play a more and more prominent role in today's society. A continuously increasing traffic demand can be observed almost everywhere whereas the supply of infrastructure is remaining nearly constant, especially in the developed countries. Therefore, the better use of the already available road network and the optimization and extension of road capacities is the major focus nowadays and in the near future. Keeping that in mind, it is a crucial task for traffic control and management to determine in time the localization of bottlenecks and temporal reductions of capacities to be able to directly avoid their negative impacts on the traffic network – if possible – or at least to reduce their intensity and spatial propagation.

The foundation for this has to be detailed and up-to-date data on the current traffic state. Only with that information an effective reaction on imminent capacity reductions or traffic breakdowns can be realized. In addition to mobile traffic detection systems like traffic helicopters, congestion reporting volunteers or Floating Vehicle Data (FVD) stationary detectors are available like Automatic License Plate Recognition (ALPR) cameras, inductive loops, radar detectors, CCTV cameras etc. However, most of these systems have very high costs of ownership together with a mostly poor spatial or temporal coverage of detection and a complicated subsequent installation in existing infrastructure.

Since several years, the use of Bluetooth detectors for the purpose of travel time recognition achieves good results in more and more traffic-related application areas. The general idea of this technology relies on the presence of activated Bluetooth devices on board of vehicles, which can be used for vehicle identification to determine their travel times. Several studies in the past years have already shown the promising benefits of the application of Bluetooth sensors as a cheap and easy-to-use technology for determining reliable travel times on freeways and also in urban areas.

As one of the first studies on the applicability of Bluetooth sensors for travel time determination Haghani et al. (2010) state, that it is a promising method for providing reliable ground truth travel time data with a high quality comparing it to floating vehicle data in Maryland and Northern Virginia. Also Barcelo et al. (2010), based on Bluetooth sensor data from the AP-7 motorway in Spain between Barcelona and the French border, prove the quality of the travel time determination based on the detection of Bluetooth devices. In a study of Martchouk et al. (2011), where Bluetooth data was collected at the I-69 in Indianapolis, also discuss the great potential of this technology for accurate travel time determination. Aliari and Haghani (2012) show an approach for Bluetooth data validation and verification on the Interstate 95 together with an evaluation of the travel time accuracy using probe vehicle data. Araghi et al. (2012) compare three different estimation methods of Bluetooth data collection with ground truth travel time data obtained by cameras resulting in the highest accuracy for their Peak-Peak method.

Based on these experiences, within the framework of this work the traffic application of using this sensor technology for an automatic incident detection on freeways is discussed. Using Bluetooth antennas installed next to the roadway, Bluetooth devices in passing cars and trucks can be detected and re-identified by means of their globally unique MAC address identifier. Based on these detections – available at several measuring cross sections along the freeways in the North of Bavaria, a federal state in the South of Germany – a representative subset of the overall achieved travel times on selected routes can be determined. This data is used for the large scale dynamic net control system in Bavaria called “dNet Bayern”. The dNet venture consists at the moment of a total of 27 standard routes and additionally 60 alternative routes to which the drivers can be dynamically redirected in cases of lower travel times in comparison to the corresponding standard route. This re-routing advices are presented to the drivers at neuralgic decision points of the freeway network using dynamic guidance panel signs with integrated traffic state information (called “dWiSta”). For more details on the venture dNet Bayern and the used technologies see also Scharrer (2009) and Margreiter et al. (2015).

Within this paper the necessary steps towards a reliable and fast automatic incident detection is described, which is the basis for a successful application of the dynamic net control. Therefore,

chapter 2 discusses the special properties of the data gathered by the Bluetooth sensors as well as the necessary steps towards a validated data set as the basis for any further evaluation. In chapter 3 the main focus of this paper, the automatic incident detection algorithm is described in detail, consisting of several sub-steps to identify not only incidents, but also warnings and potential indicators for the end of an incident. Furthermore, chapter 4 concludes the findings on the presented algorithms and highlights the potentials of further research, to enrich the quality of detection by additionally using the rate of multiple detections at one single sensor location.

2 Bluetooth data

Starting with ten Bluetooth sensors since 2009, now more than 50 are installed in Northern Bavaria, Germany, to deliver a large amount of Bluetooth datasets containing travel times and therefore also speeds for segments of the freeway network.

A benefit of the Bluetooth detectors is the possibility to use real measured travel times for the observed freeway section in comparison to using models which are estimating and extrapolating based on values gathered from local detectors. Of course the Bluetooth data can be also merged with such local detection data to enrich the overall data quality of the travel time detection.

Like presented in Margreiter (2016), the general concept is, that the Bluetooth sensor detects the unique MAC address of activated Bluetooth devices within the detection range of the antenna. Devices that can be detected are for instance smartphones, tablets, head sets, hands free devices or cars and trucks equipped with Bluetooth interfaces. Each such single device has a unique MAC address, which therefore also works as a unique identifier for the vehicle on board of which the device is located. Directly after the detection, the MAC address of each device is cut and irreversible encrypted due to data privacy reasons, leading to a non-traceable encrypted ID. A re-identification of this encrypted ID address at a successive Bluetooth antenna forms a so-called Bluetooth pair for a segment. Together with the knowledge about the exact detection time stamps, this Bluetooth pair enables the determination of the travel time of the related vehicle between both sensor locations and therefore also the average travel speed on that segment. The result is continuous information about the prevailing travel times on the observed section of the road, since several vehicles are equipped with Bluetooth devices and deliver data.

Originated by the nature of this technology, biased travel times exist due to different devices sharing the same encrypted ID, missing detections because of sensor limitations, vehicles stopping between two detectors at freeway restaurants or service stations as well as vehicles leaving the freeway for some time at an off-ramp between the two relevant detectors and returning later. The challenge of removing this potential sources of error requires a filter which is able to remove such implausible travel times. Therefore, the “Time Dependent Comparison to Neighbor values filter” (TiDeCoNe) was introduced (see Margreiter, 2016) for the validation of Bluetooth data sets. The TiDeCoNe consists of two subsequent filtering steps. In the first step the obviously unrealistic travel times are removed based on fixed and predefined threshold values. In the second and main step, a continuously dynamic threshold filter criterion is determined based on the two temporally neighboring detections. This filter, including several data validation steps, leads to a cleaned data set of speed values. Using this data set the present work describes the realized automatic incident detection algorithm to determine the temporal and spatial occurrence of congestions in the freeway network. The presented algorithm aims at detecting incidents on German freeways fast and reliable. Therefore, several parameters and variables are used to calibrate the sensitivity of the Automatic Incident Detection (AID) algorithm. The AID continuously analyses a past time segment of variable length and compares the determined traffic related parameters with ex-ante defined threshold values. The specifics are explained more in detail in the following chapter.

3 Automatic incident detection methodology

For each valid detection of a Bluetooth pair between two subsequent detectors, the incident detection algorithm is started again to observe if this new detection is an indicator for a change in the prevailing traffic state. Therefore, the approach described in the following is started whenever a new detection has passed the validity tests described in chapter 2.

The whole detection algorithm is based on a set of majorly three variables which are influencing the determination of an incident. These variables are:

- Number of detected active Bluetooth pairs – further on also indicated as detections – in a certain observed time segment.
- Determined mean speed at the observed section within the observed time segment.
- Determined maximum speed at the observed section within the observed time segment.

In the following these three values, their calculation and their importance for the further steps of the algorithm are discussed.

Number of detected active Bluetooth pairs in a certain observed time segment:

The first variable symbolizes the quantity of detected and re-identified devices at the observed section, which also passed the validity tests and filtering steps mentioned in chapter 2. This parameter includes only detections which also happened within the currently observed time segment T_p . The time segment T_p is a rolling time window being re-calculated for each new determined Bluetooth pair. The allocation of a detected Bluetooth pair to a certain time segment is done using the average time stamp of the device's detections at the first of the two Bluetooth sensors of the actual section.

The length of the time segment T_p is also available as a flexible parameter for further calibration, to optimize the trade-off between the time needed for a valid detection and the reliability of the detection itself.

Using this variable has the aim to avoid, that already a very small group of slow vehicles (e.g. few slow trucks at night) can trigger an incident detection. If an observed time segment contains too less single detections to determine the further variables, the time segment is extended accordingly. This enables a larger set of detected vehicles for the calculation of the relevant parameters for the incident detection algorithm. To avoid falsification of the actual situation on the road by looking too far in the past, this step-wise extension of the time segment is limited.

The parameter value for the marginally needed quantity of detections in a time segment for the calculation of the further variables is currently set to five vehicles. With an initial length of 120 seconds, the time segment T_p can be extended stepwise by another 120 seconds in cases where there are still less than five detected vehicles within the observed time period. The maximum extension of the current time segment is set to a factor of five. Therefore, the maximum time segment length is limited to ten minutes, to allow only current vehicle travel times to have an impact on the algorithm results, even in cases with a very low number of detections.

In Figure 1 the previously described procedure to choose a valid time segment length T_p and to determine the relevant number of detections within this time segment is shown in a flow chart, with the currently defined parameters values of:

- t_0 = 120 seconds
- $q_{T,\min,seg}$ = 5 detections
- $t_{T,\max}$ = 600 seconds

Generally, the variable $q(T_p)_{AB}$ for the number of detected active Bluetooth pairs, therefore is also defining the length of the actual observed time segment T_p . For each new detection which is passing the validity tests, the previous time segment is determined and the two major parameters of the algorithm are calculated, which are described in the following paragraphs.

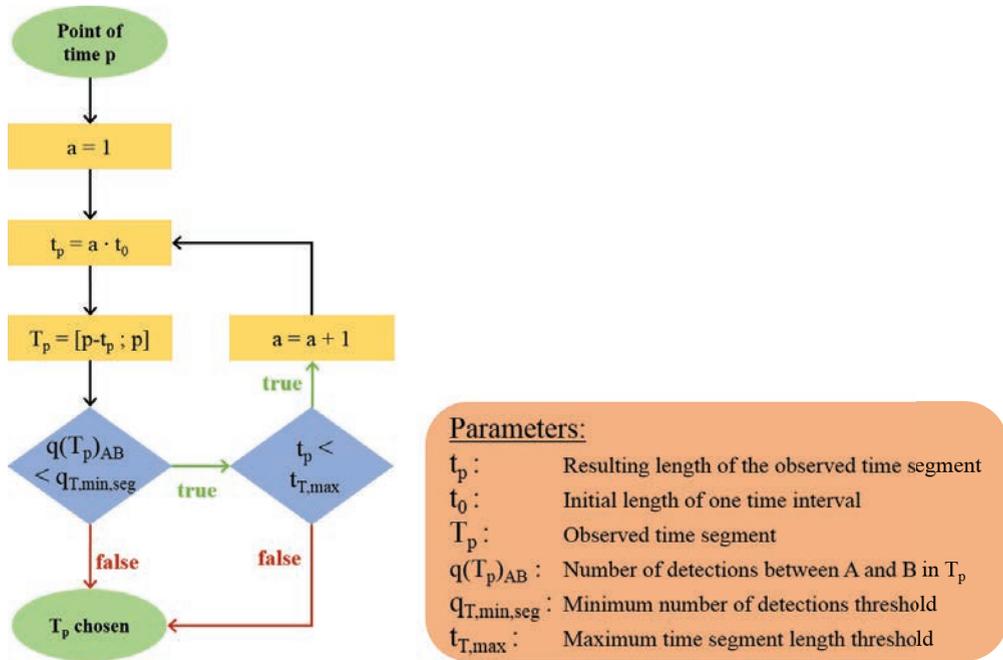


Figure 1: Flow chart for the determination of the correct time segment T_p

Mean speed at the observed section:

As an additional variable to detect an existing traffic incident at an observed section of a freeway, the mean value of the achieved speeds of the detected Bluetooth devices between the two boundaries of the section is used. This variable symbolizes the average speed of all Bluetooth pairs travelling from Bluetooth sensor A to sensor B, having the first detection time stamp at sensor A within the observed time segment T_p and is calculated as follows:

$$v(T_p)_{AB,mean} = \frac{q(T_p)_{AB} \cdot l_{AB}}{\sum_{i=0}^{n(T_p)_{AB}-1} tt(i)_{AB}} \cdot 3.6 \quad \text{with } tt(i)_{AB} \in T_p$$

where:

- T_p = Observed time segment which is ending at point of time p
- $v(T_p)_{AB,mean}$ = Mean speed from sensor A to B within time segment T_p [km/h]
- l_{AB} = Length of the section between A and B [m]
- $q(T_p)_{AB}$ = Quantity of detected Bluetooth pairs at the section from A to B within T_p [det]
- $tt(i)_{AB}$ = Travel time of the Bluetooth pair i from A to B [s]

Maximum achieved speed:

It is assumed, that in case of a relevant incident situation all lanes at the freeway are affected. Therefore, apart from a reduction of the mean speed at the congested road section also a decrease in the maximum achievable speeds will be observable. Due to that, also this maximum speed in the observed time segment between the two Bluetooth sensors is taken into consideration as an additional variable, necessary for the incident detection algorithm. The following formula shows how the maximum achieved speed is determined in this case:

$$v(T_p)_{AB,max} = \frac{l_{AB}}{\min[tt(i=0)_{AB} \dots tt(i=q(T_p)_{AB}-1)_{AB}]} \cdot 3.6 \quad \text{with } tt(i)_{AB} \in T_p$$

where:

- T_p = Observed time segment which is ending at point of time p
- $v(T_p)_{AB,max}$ = Maximum speed from sensor A to B within time segment T_p [km/h]
- l_{AB} = Length of the section between A and B [m]
- $tt(i)_{AB}$ = Travel time of the Bluetooth pair i from A to B [s]
- $q(T_p)_{AB}$ = Quantity of detected Bluetooth pairs at the section from A to B within T_p [det]

The automatic incident detection itself, is based on the comparison of these three variables with certain threshold values. It consists of three parts, which are describing the potential change and also the approved change from one traffic state to another. The current version considers the two traffic states free flow traffic and congested traffic and therefore contains the following detectable phases:

- Determination of an incident warning.
- Determination of an incident.
- Conditions for a detected end of an incident.

These phases or steps of the algorithm are discussed in details in the subsequent subchapters.

3.1 Determination of an incident warning

Based on the application area of a dynamic net control within the Bavarian freeway network the detection of an incident based on Bluetooth data has to fulfil several conditions. One of the most important ones is the reliability and validity of the detection of an incident. Therefore, the algorithm has to be really sure about an incident before forwarding the detected congestion or capacity reduction to the net control system. On the other hand, the detection has to be fast, to also be able to react almost in real time when changing the route guidance signs on the freeways to reroute vehicles to better routes with a shorter travel time. A solution for that trade-off between a fast and a reliable incident detection was realized within this research project via the implementation of an additional warning phase, which identifies potential incident situations, which might lead to a reliably detected incident soon. Therefore, the warning phase is a not yet validated indicator for a possible congestion or capacity reduction in the next seconds or minutes.

The warning state is based on the previously described three major variables and is determined by the verification of three conditions these variables have to fulfil:

$$\text{Condition 1: } q(T_p)_{AB} \geq q_{T,min,warn} \cdot \frac{t_p}{3600s/h}$$

$$\text{Condition 2: } v(T_p)_{AB,mean} < v_{T,mean,warn}$$

$$\text{Condition 3: } v(T_p)_{AB,max} < v_{T,max,warn}$$

where:

- $q(T_p)_{AB}$ = Quantity of detected Bluetooth pairs at the section from A to B within T_p [-]
- $v(T_p)_{AB,mean}$ = Mean speed from sensor A to B within time segment T_p [km/h]
- $v(T_p)_{AB,max}$ = Maximum speed from sensor A to B within time segment T_p [km/h]
- $q_{T,min,warn}$ = Minimum detections threshold [det/h]
- $v_{T,mean,warn}$ = Mean speed threshold [km/h]
- $v_{T,max,warn}$ = Maximum speed threshold [km/h]

These three conditions are checking, if the number of Bluetooth pairs exceeds the minimum threshold value of necessary Bluetooth detections, if the mean speed at the section is dropping below the threshold speed for a warning and if the maximum achievable speed threshold is undershot in the time segment. They are also shown in the following flow chart:

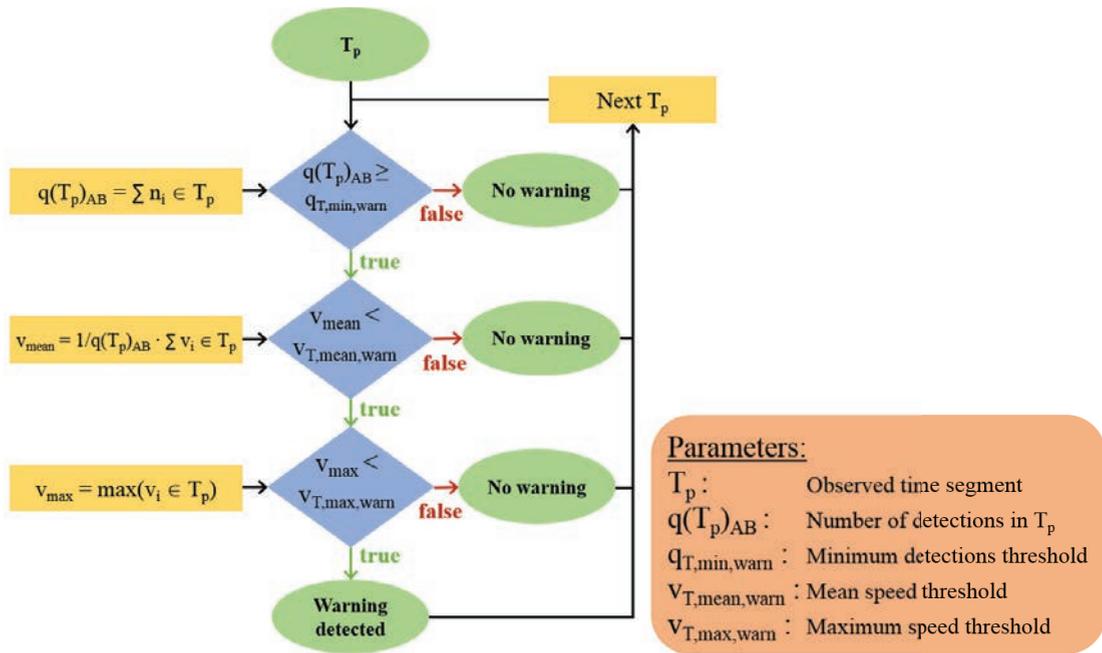


Figure 2: Flow chart for the determination of an incident warning

The related threshold values are set to:

- $q_{T,min,warn} = 60$ detections/h
- $v_{T,mean,warn} = 80$ km/h
- $v_{T,max,warn} = 100$ km/h

If all three conditions are fulfilled at the same time for the same new detection, the warning phase is activated and the algorithm is continuing to search for further subsequent indicators for a potential incident by checking the next detected Bluetooth device.

3.2 Detection of an incident

For the detection of a verified incident, the conditions are stricter than for the detection of a warning of a potential incident. Additionally, an incident detection can just be verified if a number of subsequent warnings has already shown the succession of a building up of a congestion or capacity reduction.

The four main conditions for the identification of an incident at a freeway section within a time segment T_p are described as follows:

- Minimum number of detected Bluetooth pairs exceeded.
- Mean speed at the section is below a certain threshold.
- Maximum achievable speed within the time segment undershoots a threshold.
- Minimum number of already detected incident warnings exceeded.

Written as formulas, the conditions in detail are:

Condition 1: $q(T_p)_{AB} \geq q_{T,min} \cdot \frac{t_p}{3600s/h}$

Condition 2: $v(T_p)_{AB,mean} < v_{T,mean}$

Condition 3: $v(T_p)_{AB,max} < v_{T,max}$

Condition 4: $n_{warn} \geq n_{T,warn}$

where:

- $q(T_p)_{AB}$ = Quantity of detected Bluetooth pairs at the section from A to B within T_p [-]
- $v(T_p)_{AB,mean}$ = Mean speed from sensor A to B within time segment T_p [km/h]
- $v(T_p)_{AB,max}$ = Maximum speed from sensor A to B within time segment T_p [km/h]
- n_{warn} = Current number of subsequent warning indicators in the past [-]
- $q_{T,min}$ = Minimum detections threshold [det/h]
- $v_{T,mean}$ = Mean speed threshold [km/h]
- $v_{T,max}$ = Maximum speed threshold [km/h]
- $n_{T,warn}$ = Threshold for subsequent warnings until an incident is detected [-]

Generally the incident detection structure (which is also shown in the following flow chart diagram in Figure 3) looks similar to the determination of a warning. Additionally, to the different threshold values which are applied, the number of already subsequently detected warnings has a major influence towards a verified detection.

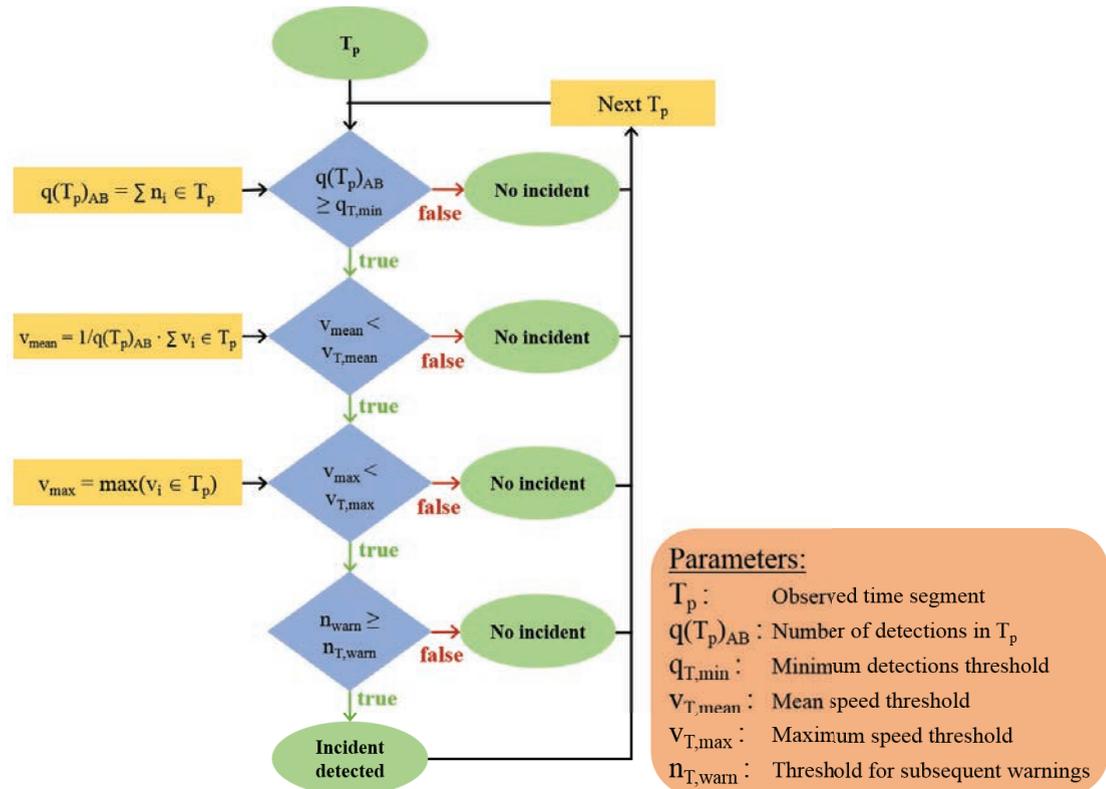


Figure 3: Flow chart for the detection of an incident

The threshold values which are the basis for this step are:

- $q_{T,\min} = 60$ detections/h
- $v_{T,\text{mean}} = 60$ km/h
- $v_{T,\text{max}} = 100$ km/h
- $n_{T,\text{warn}} = 20$ subsequent warnings

After more than 20 warnings in a row without any single outlier in the meanwhile, it is checked if the mean speed has decreased below the stricter threshold $v_{T,\text{mean}}$ which is set to 60 km/h. If this is fulfilled the incident detection is verified.

3.3 Conditions for a detected end of an incident

Not only the start but also the end of an incident situation is of big importance in the context of a dynamic net control system. To be able to discontinue the change in the route advice due to a traffic incident in the freeway, exact knowledge about the change of the traffic state back to free flow traffic is of great relevance. Within this approach the detection of an incident end is comparable to the detection of the start.

Therefore, also the conditions of such an incident end are similar and mainly symbolize the reverse comparison to threshold values:

$$\text{Condition 1: } q(T_p)_{AB} < q_{T,\min} \cdot \frac{t_p}{3600s/h}$$

$$\text{Condition 2: } v(T_p)_{AB,\text{mean}} \geq v_{T,\text{mean}}$$

$$\text{Condition 3: } v(T_p)_{AB,\text{max}} \geq v_{T,\text{max}}$$

$$\text{Condition 4: } n_{\text{end}} \geq n_{T,\text{end}}$$

where:

$q(T_p)_{AB}$	=	Quantity of detected Bluetooth pairs at the section from A to B within T_p [-]
$v(T_p)_{AB,\text{mean}}$	=	Mean speed from sensor A to B within time segment T_p [km/h]
$v(T_p)_{AB,\text{max}}$	=	Maximum speed from sensor A to B within time segment T_p [km/h]
n_{end}	=	Current number of subsequent potential indicators for an incident end [-]
$q_{T,\min,\text{end}}$	=	Minimum detections threshold [det/h]
$v_{T,\text{mean},\text{end}}$	=	Mean speed threshold [km/h]
$v_{T,\text{max},\text{end}}$	=	Maximum speed threshold [km/h]
$n_{T,\text{end}}$	=	Threshold for subsequent potential indicators until an incident is discontinued [-]

Just like for the detection of an incident, also the detection of the end has to be proven by the subsequent appearance of potential indicators ($n_{T,\text{end}}$) until it leads to an annulment of the incident phase. The parameter set for this is shown below:

- $q_{T,\min,\text{end}} = 60$ detections/h
- $v_{T,\text{mean},\text{end}} = 60$ km/h
- $v_{T,\text{max},\text{end}} = 100$ km/h
- $n_{T,\text{end}} = 20$ subsequent potential indicators for an incident end

Generally, a detected incident always requires a prior warning phase and is always discontinued by a potential indicator phase for the end of an incident. On the other hand, this means, that a warning phase is not always necessarily leading to an incident detection. Also a potential indicator phase for

the end of an incident does not have to result in a discontinued incident phase, but can just be a short relaxation of the traffic state, directly leading back to a congested traffic state.

The following Figure 4 shows an example evaluation of an incident situation at the freeway A6 south of Nuremberg.

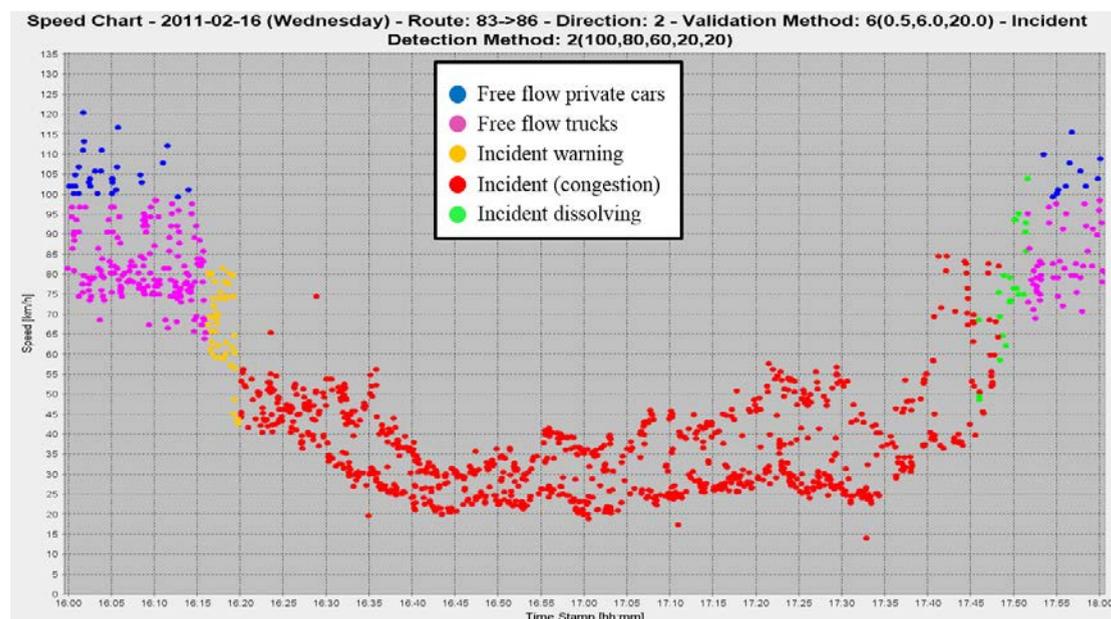


Figure 4: Example of an incident detection on the German freeway A6 based on Bluetooth detections

Each colored dot in the plot symbolizes a determined speed value of one single validated Bluetooth detection pair between two subsequent detectors. Magenta and blue dots are indicating private cars or trucks in free flow conditions, roughly classified based on their achieved speeds, whereas the red coloring stands for speed values which are in the phase of a detected incident. The warning phase, shown in orange, in this example directly leads to a succeeding incident detection at around 16:20. The few potential indicators for an incident end in green at 17:45 are not directly leading to an incident end, but are followed again by some lower speed values to interrupt the incident end phase. Some minutes later, starting at 17:48 the continuously higher speed values lead to a longer subsequent occurrence of potential indicators, discontinuing the incident phase and going back to the traffic state free flow at approximately 17:52.

In the figure also the achieved speeds on the two different lanes of the freeway during the incident are visible, by looking at the accumulation of values in the upper and the lower boundary of the cloud of values in red.

4 Conclusions and further research

The present paper describes the application of an automatic incident detection algorithm based on Bluetooth travel time data input in the freeway network of Bavaria. Since the outcome of this algorithms are used for a dynamic net control the approach was developed to be fast in the detection of upcoming congestions and capacity reductions and also reliable in terms of avoiding false alarms. Therefore, it consists of three subsequent steps leading to an incident detection with different phases:

- The detection of an incident warning, which points to a potential incident situation which might occur soon.
- The detection of the incident itself, which necessarily has to have a preceding warning phase.
- The detection of indicators of a potential end of an incident situation and its negative impacts, which always has to follow a detected incident to discontinue this phase.

The paper also shows the relevant variables which need to be determined and checked against threshold values within the framework of the algorithm. Those variables can be determined solely based on the existing and available data from Bluetooth sensor networks. Also a typical and well tested parametrization of the relevant threshold values is presented.

A potential additional parameter to make the Bluetooth detection of incidents even faster is the rate of multiple detections. This rate indicates the average of how often the identical Bluetooth MAC address was identified at the same sensor while passing the sensor's detection area. Typically, the Bluetooth broadcasting pulse frequency is 1.26 seconds, which means that depending on the vehicle speed a device can be detected every 1.26 seconds as long as it is still in the detection area of the Bluetooth scanner. This parameter can – in comparison to the other discussed variables in this paper – not be determined per direction, since the measurements of one single Bluetooth antenna cannot be used to reconstruct the direction of travel of the detected device. Nevertheless, an increase in this rate can be used as an indicator, that the equipped vehicles which are passing by, spend a longer period of time in the detection area of the sensor, which allows to conclude a lower speed of these vehicles or even a longer standstill phase due to a congestion in the sensor coverage area. Therefore, such an increase of the multiple detection rate very often indicates the occurrence of an incident, directly upstream or downstream of the sensor location. An example of such a typical increase of the rate of multiple detections in an incident situation is shown in the following Figure 5.

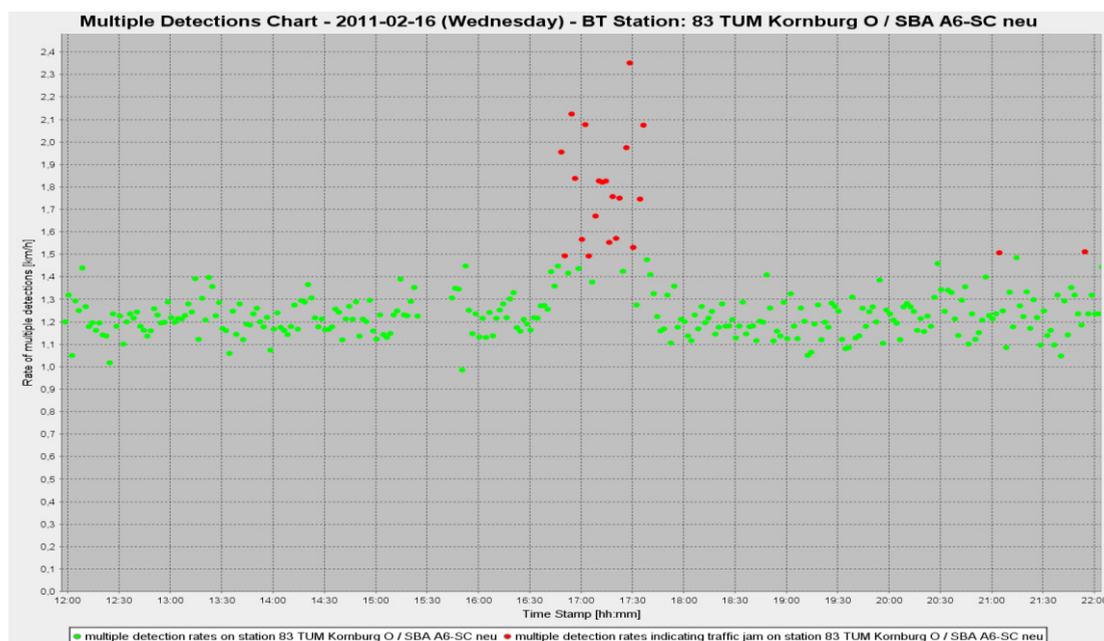


Figure 5: Example of an increase of the rate of multiple detections at one sensor

It can be seen that approximately between 16:45 and 17:35 an increase in the rate of multiple detections can be observed (indicated by the change of color from green to red). Empirically one can

state, that above a multiple detection rate of 1.50 the probability of having a real incident in the antenna coverage area is very high.

Further research is currently ongoing to determine the potential of using this rate as an additional parameter in the algorithm to make the incident detection based on Bluetooth even faster in terms of reaction time and also more reliable. A constraint which is worth to mention here, is, that this approach is only applicable if the incident or its effects are directly located within the coverage area of the Bluetooth sensor. If the congestion related shockwave has not yet arrived at the sensor position, a change in the rate of multiple detections will not be measurable since the speeds will not be reduced significantly.

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References

- Aliari, Y., & Haghani, A. (2012). Bluetooth Sensor Data and Ground Truth Testing of Reported Travel Times. *Transportation Research Record*, 2308, pp. 167-172.
- Araghi, B. N., Christensen, L. T., Krishnan, R., & Lahrmann, H. (2012). Application of Bluetooth Technology for Mode Specific Travel Time Estimation on Arterial Roads: Potentials and Challenges. *Proceedings from the Annual Transport Conference at Aalborg University*.
- Barceló, J., Montero, L., Marqués, L., Marinelli, P., & Carmona, C. (2010). Travel Time Forecasting and Dynamic OD Estimation in Freeways based on Bluetooth Traffic Monitoring. *Transportation Research Record Journal of the Transportation Research Board* 2175(2175).
- Haghani, A., Hamed, M., Sadabadi, K. F., Young, S., & Tarnoff, P. (2010). Data Collection of Freeway Travel Time Ground Truth with Bluetooth Sensors. *Transportation Research Record, Journal of Transportation Research Board, Vol 2160, pp 60-68*.
- Margreiter, M. (2010). Travel Time Determination and Automatic Incident Detection using Bluetooth Detection. *Master's Thesis at the Chair of Traffic Engineering and Control, Technische Universität München*.
- Margreiter, M. (2016). Fast and Reliable Determination of the Traffic State Using Bluetooth Detection on German Freeways. *World Conference on Transport Research, Shanghai, China (submitted and accepted for publication)*.
- Margreiter, M., Spangler, M., Zeh, T., & Carstensen, C. (2015). Bluetooth Measured Travel Times for Dynamic Re-Routing. *3rd Annual International Conference Proceeding on ACE, Volume 2, Global Science and Technology Forum, Singapore*.
- Martchouk, N., Mannering, F., & Bullock, D. (2011). Analysis of Freeway Travel Time Variability Using Bluetooth Detection. *Journal of Transportation Engineering* 137(10): 697-704.
- Scharrer, R. (2009). Dynamic Network Control Bavaria - dNet Bavaria. *mobil.TUM International Scientific Conference on Mobility and Transport, Munich, Germany*.