THE EVOLUTION OF BLUETOOTH DETECTION RATES

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ABSTRACT
Bluetooth detection is a valuable source to gather data about travel times and traffic state in road networks aiming for the goals of better traffic information and traffic management. Just like for all other available traffic data sources, road operators and authorities rely on a reliable quality of the data collection to fulfil their goal of higher traffic efficiency. First, this data quality depends on the reliability of each individual data set and second on the quantity of data sets, specified by the detection rate. Whereas the quality of Bluetooth-detected travel times has already been discussed in several studies, this research investigates the evolution of detection rates over the past decade in the freeway network of the state of Bavaria, Germany. The objective is to provide reliable information about the current potential and the current trends in the detection rates to road authorities who plan the installation of Bluetooth detection technology. For this purpose, the detection rates, defined by the share of detected vehicles with Bluetooth amongst the overall traffic volume measured with induction loops, were evaluated for this study. The results based on more than 1.7 billion individual Bluetooth detections show a quite steady Bluetooth detection rate of around 25 % since the beginning of measurements in 2009. Additionally, the results show a large systematic bias within the data due to the higher equipment rate with Bluetooth devices amongst trucks, which are equipped about five times more often than regular passenger cars.

Keywords: Bluetooth, Detection Rate, Sample Rate, Penetration Rate, Freeway

MOTIVATION

As traffic demand steadily grows worldwide, the need to operate and manage road networks in a more efficient and resilient way is getting more and more important. This requires up-to-date and network-wide information about the current traffic situation to be able to roll out counter measures to control and minimize the negative effects on the overall transportation network in case of incidents.

This information is traditionally gathered by stationary local detection technologies like inductive loops or local sensors based on radar, laser, infrared, ultrasonic or video technology. In comparison to these local detection systems, which are measuring fundamental traffic flow parameters like traffic volume, occupancy rate or local speeds of vehicles, also segment-based detection methods exist. A characteristic of segment-based sensors is that the gathered data represents information for the whole segment between two detectors and not only for the location of the detector itself. Therefore, with this kind of detection the collection of travel times and travel speeds can contribute information for the entire network and not only for certain points in the network. This data can then be used for determining the traffic state and detect incidents within the network *(1),* which is the basis for large-scale dynamic rerouting of long-term travelers in case of incidents *(2)*. Examples of such segment-based detection technologies are Automatic Number Plate Recognition (ANPR) systems or the detection of vehicles using Bluetooth technology. This paper mainly focuses on the latter system.

However, there is still a big need for reliable data about the characteristics of such new detection technologies based on Bluetooth for road operators and freeway management centers who are currently looking for new ways to gather necessary data about traffic flow and traffic state. Several authorities have already decided to implement Bluetooth detection technology for travel times or are considering it as a valid option in the next years. Having said this, there is still reliable information missing about how trustful the results from Bluetooth are at the end.

This paper aims at providing this reliable data for researchers and practitioners in the field of traffic data collection. Therefore, this study is based on data from several years and covers a large freeway network. The aim is providing detailed information of the realizable detection rates on freeways using Bluetooth detection technology.

DATA

The fundament for traffic data collection based on Bluetooth are electronic devices which are carried by travelers. These devices are for example cell phones, smart phones, hands-free sets, tablets but also the Bluetooth interfaces of entertainment systems within vehicles. If the Bluetooth interface (IEEE 802.15.1 standard) of those devices is activated and visible, other Bluetooth-capable platforms can recognize them. In the field of transportation, this characteristic is used to detect and re-identify travelers moving in the transportation network. For motorized traffic on freeways, the movements of the traveler carrying the Bluetooth device is considered identical to the movements of the vehicle. Therefore, this can be used to detect and determine several direct and indirect traffic parameters. For the purpose of Bluetooth detection on freeways, dedicated Bluetooth scanners are installed at fixed locations next to the freeway. Equipped with omni-directional or directional antennas these scanners detect Bluetooth devices located on board of passing vehicles. A so-called ‘handshake’ between the scanner and the device in the passing vehicle is carried out, leading among other information to the exchange of the unique physical hardware address of the two network adapters. This hardware address is known as the MAC

(Media Access Control) address and is represented by a 48-Bit code which is normally written in a 6-Byte 12-digit hexadecimal format. The first six hexadecimal digits are hereby representing the manufacturer of the device (OUI – Organizational Unique Identifier) whereas the remaining six digits should be allocated by the manufacturer itself as the device's series number. According to the specifications of the IEEE (Institute of Electrical and Electronics Engineers) each network adapter should have a worldwide unique MAC address. In principle, this allows to identify and re-identify each device on its way through the traffic network. Despite the aforementioned IEEE specifications, in reality there are numerous cases where several different devices are having an identical MAC address. Such addresses have to be identified and isolated, because otherwise they will bias the overall dataset with false travel times generated from an observation of two different devices sharing the same MAC address. For this reason, a blacklist is created every day containing the affected MAC addresses.

Having said this, the detected MAC address together with the exact detection time stamp represents the pass-by of a vehicle with the Bluetooth device on board at the Bluetooth scanner location. If the same vehicle passes by a second detector the MAC address can be re-identified and both Bluetooth detections can be matched to form a movement chain from first to second detector. Based on the time difference between the two detections at two consecutive scanners the travel time between both locations can be determined. Since also the static distance between both detector locations should be known the distance-related reciprocal travel speed can be calculated. The following figure 1 shows the Bluetooth detection principle.

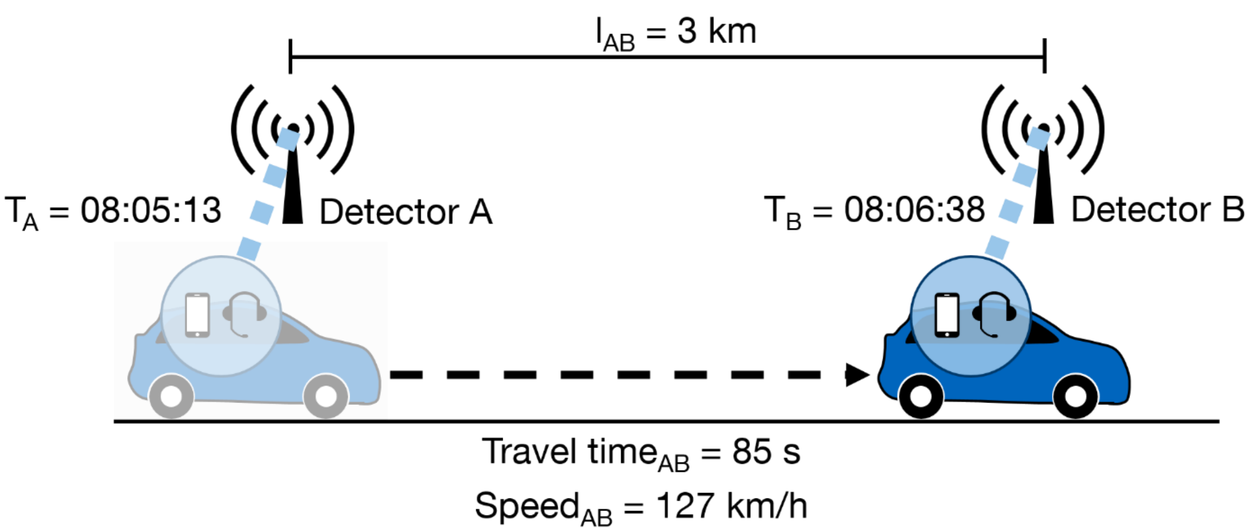

FIGURE 1 Bluetooth detection principle.

Due to German data protection regulations the detected MAC addresses are first shortened and then irreversibly encrypted directly at the scanner itself to a hash ID. This prevents the identification of the traveler's identity as well as the tracking of travelers over a longer period since the encryption mechanism is changed every 24 hours.

In general, not every detected Bluetooth device corresponds exactly to one vehicle because several activated Bluetooth devices can be located on board of just one single vehicle. Furthermore, faulty detections or other errors caused by the driving behavior between the detector locations may lead to incorrect or falsified travel times which lead to an increased number of travel time outliers. Figure 2 shows some of those possible errors such as:

- Vehicles receiving the same hash ID due to the above-mentioned shortening and encryption of the MAC address: (a).
- Incorrect assembly of vehicle routes due to missing detections: (b).
- Vehicles that interrupt their journey between two detectors for example at a freeway rest area: (c).
- Vehicles leaving the freeway for a short time and continuing their trip later: (d).

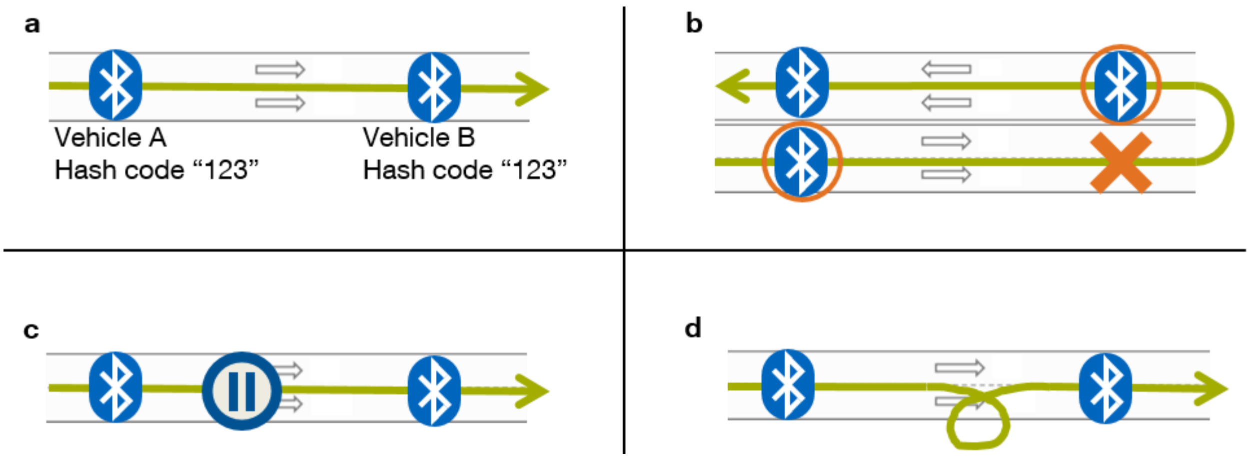

FIGURE 2 Potential sources of error, biasing the correct determination of travel times.

In addition, there are potential sources of error in the detection due to the large detection area of the Bluetooth scanner (defined by the range of the used antenna(s)). The result is that the same Bluetooth device can be detected several times while passing by. A clear correlation between the detection time and the position of the vehicle within the coverage area of the scanner antenna is not possible (see figure 3).

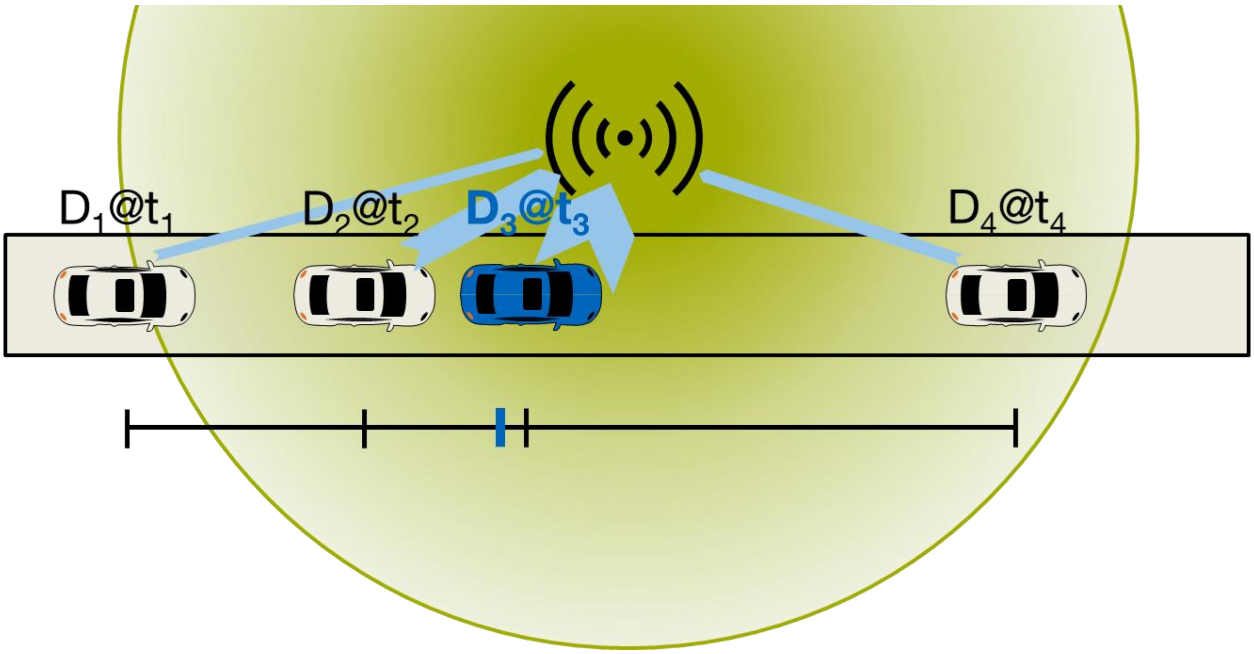

FIGURE 3 Schematic coverage area of the antenna with one vehicle passing through.

For these reasons, it is important to use a Bluetooth data preparation method which eliminates those technology-specific errors. In addition, an outlier filter algorithm is needed which is calibrated on the specifics of Bluetooth data in order to be able to correct the negative influences on the travel time determination later. For this purpose, the TUM-AID algorithm *(3)* was used for this present study. It additionally implements an integrated traffic state and automatic incident detection to identify disruptions in the traffic flow spatially and temporally based on travel time values from the Bluetooth detections which was not used for this present study. By using this algorithm, all of the above-mentioned potential error sources can be controlled.

The dataset, which was analyzed for this study, ranges from March 2009 to November 2017 and covers more than 3,000 individual days of data within these nine years of detection. More than 1.7 billion single Bluetooth datasets were detected during that period leading to a significant sample size for this study.

The data was collected in the freeway network of Northern Bavaria, Germany, where currently almost 200 Bluetooth detectors are installed next to the freeways A3, A6, A7, A9, A70, A71 and A73. The Bluetooth data was provided by the Bavarian Center for Traffic Management (ZVM) and the Motorway Directorate of Northern Bavaria (ABDN).

For the determination of the detection rates, permanently installed inductive loops were used as the ground truth for the real traffic volumes. These traffic volume counts are available through the German Federal Highway Research Institute (BASt).

EXISITING WORK

A vast amount of literature is already available showing Bluetooth detection rate results from mostly isolated and small test sites over a short period of time and therefore with a low sample size.

A study at the University of Maryland (4) (5) in 2010 which was conducted on several freeway segments in Delaware and Maryland found out that the average hourly Bluetooth detection rate amounts for values between 2 % and 5.4 % in Delaware and between 2 % and 8.1 % in Maryland.

In the south of Aalborg, Denmark, a 2012 test (6) with two BlipTrack Bluetooth detectors on a segment with 550 meters resulted in a Bluetooth detection rate of 4.5 % in uncongested traffic. The authors claim, that they would have expected a higher detection rate of 20 %, like in their previous studies. Their explanation for this difference was the sub-optimal location of the sensors on the ground due to which the detection rate was significantly reduced by the decreased size of the resulting detection zone.

The University of Maryland together with the Indiana Department of Transportation conducted a study (7) in the U.S. in 2009 resulting in detection rates on a freeway of 5 % to 7 %.

On urban freeways in the metropolitan area of Barcelona, Spain, the authors of a 2010 study (8) evaluated a detection rate of 30 % and used this value for their simulation experiment.

The Queensland University of Technology has conducted several studies (9), (10), (11), (12) in the area of Brisbane, Australia, using Bluetooth detectors next to freeways. In 2013, they determined a detection rate of 3 %, whereas in 2015 the detection rate was already 5 %. Additional findings from the Brisbane freeway led to the conclusion that around 10 % of the Bluetooth observations were missed in a daily data set.

According to another research study (13), several trials in the Netherlands resulted in detection rates of 25 % to even 40 %. The authors also conducted individual tests at the Dutch freeways A6, A7, A31 and A32 showing very high detection rates of 54 %, 62 % 70 % and 61 % respectively.

A more detailed field test (14) was conducted in Brisbane, Australia, to find out the real penetration rate of vehicles with Bluetooth technology. Therefore, the authors manually analyzed 110 vehicles at the Mt-Cootha Road in Brisbane. The analysis showed that 31 % of all passenger cars had one detectable Bluetooth device on board whereas only 5 % carried two devices. No cars were observed having more than two devices. Amongst commercial vehicles they state a much higher penetration rate even though the sample (only 9 % traffic share) was too small for a valid statement. Amongst all vehicles, the penetration rate was 38 %, which represents the maximum possible detection rate. The resulting detection rates ranged from 5 % to 40 % across 29 different locations with a mean value of 20 %. Additionally, the authors tested the installation of two Bluetooth antennas at once at one single detector location and were able to increase the detection rate by up to 7 %.

The Purdue University evaluated five Bluetooth sensors deployed in December 2008 for continuous 24-hour detection, resulting in 5 % to 10 % of discoverable Bluetooth MAC addresses at the Interstate 65 in Indianapolis with two lanes in each direction. Another study by the same author conducted at the Indianapolis International Airport in 2009 (16) tested the Bluetooth detection rate amongst pedestrians in the airport building. This approach demonstrated that 5 % to 6.8 % of the passengers carry a detectable Bluetooth device with them.

In a white paper for the Florida Department of Transportation (17) the authors state that the Bluetooth matching rate is generally in the 5 % range for most areas in the U.S.

The Tennessee Tech University established a test site at the Interstate 40 in Cookeville, Tennessee around 130 kilometers east of Nashville with Traffax BlueFax Portable Bluetooth detectors (18). This test in 2006 showed Bluetooth detection rates between 4.73 % and 6.9 % with an average of 6.25 %.

In another study in 2010 by the Purdue University (19) the authors state that in average a Bluetooth detection rate of about 10 % can be observed.

The Wisconsin Department of Transportation together with the University of Wisconsin-Milwaukee tested Bluetooth detection rates at work zones in the year 2013 (20). For this purpose, work zones at the I-39, I-90 and I-94 in west-central Wisconsin, in Milwaukee County and in Waukesha County were equipped with Bluetooth sensors. At low traffic volumes the work zones showed a Bluetooth detection rate between 0.2 % and 3.6 % whereas during higher traffic volumes the values increased to 1.7 % to 5.7 %. They report that the reason for a higher detection rate in denser traffic is the longer time duration the vehicles spend in the detection area when driving with lower speed.

In the city of Porto in Portugal the University of Porto observed a Bluetooth detection rate of around 20 % in the year 2014 (21).

The following table shows all above-mentioned Bluetooth detection rates as a summary and sorted by their average from low to high.

TABLE 1 Available Bluetooth detection rates from literature.

Reference	**Year**	**Country**	**Detection rate**
(20)	2013	U.S.	0.2 % - 5.7 %
(9) (10) (11) (12)	2013	Australia	3 %
(4) (5)	2010	U.S.	2 % - 5.4 %
(6)	2012	Denmark	4.5 % (expected: 20 %)
(17)	2012	U.S.	5 % (matching rate)
(9) (10) (11) (12)	2015	Australia	5 %
(4) (5)	2010	U.S.	2 % - 8.1 %
(7)	2009	U.S.	5 % - 7 %
(18)	2006	U.S.	6.25 %
(15)	2008	U.S.	5 % - 10 %
(19)	2010	U.S.	10 %
(21)	2014	Portugal	20 %
(14)	2010	Australia	5 % - 40 %
(8)	2010	Spain	30 %
(13)	2012	Netherlands	25 % - 40 %
(13)	2012	Netherlands	54 % - 70 %

The results clearly show a vast variety of different Bluetooth detection rates. One reason for those deviations might be the use of wrong sensor types or antennas for some tests as well as an inappropriate installation and orientation of the antenna(s) itself. Most of these tests were conducted with different Bluetooth sensors with different boundary conditions, like antenna type, antenna installation height, position and angle as well as different prevailing traffic conditions and road types.

In addition, it can be observed that clearly higher detection rates are given for several European countries in comparison to the U.S.

Even though in most of the studies the traffic volume does not have a significant impact on the detection rates, it has to be considered that resulting lower travel speeds certainly do. The lower the speed of the vehicle, the longer the Bluetooth device is present in the antenna coverage area leading to a higher probability of detection. The theoretical maximum of the detection rate is the penetration rate with Bluetooth devices.

METHODOLOGY

Based on the data described two sections before, the Bluetooth detection rates of the Bluetooth scanners in the freeway study area in Northern Bavaria, Germany were determined within this present study.

The parameter detection rate is used because the real equipment rate with Bluetooth devices on board of passing vehicles cannot be determined directly with the use of Bluetooth scanners.

There are two main reasons for this:

- There are Bluetooth-enabled devices in vehicles with the radio interface being disabled or changed to invisible mode by the user.
- Even with an activated and visible Bluetooth interface it is not ensured that each device is also detected by the roadside sensors. Perhaps it might not be detected for reasons like shading or occlusion depending on the location of the device within the vehicle.

Therefore, the Bluetooth detection rate represents the share of the entire vehicle collective which is actually being detected with active Bluetooth devices and which can be used for a further determination of resulting traffic parameters.

Despite a consideration across multiple sites the Bluetooth detection rate is a purely local characteristic of a single detector site. In addition, the detection rate always includes both directions of travel detected by the Bluetooth scanner because at an isolated Bluetooth detector site no determination of the direction of travel of the detected vehicles is possible. For this reason, the ground truth for traffic volumes from the local detectors of the BASt are also used for both directions of travel to calculate the correct detection rates.

The locations at which the detection rates were determined were selected to minimize potential external interferences. Therefore, locations were not taken into considerations which:

- had a long spatial distance between location of the Bluetooth detector and the related inductive loop detector as a ground truth reference (the closer both locations are, the more comparable their values are),
- had a freeway interchange or on- and off-ramps between the reference inductive loops and the Bluetooth detector (with the possibilities for cars to leave the freeway between the two locations, the data would have not been comparable),
- were close to a residential area, rest areas, parking lots or other streets, which would generate irrelevant detections from outside the freeway within the antenna coverage area of the Bluetooth sensor, or

- had Bluetooth detectors, which have often been replaced or relocated by the freeway authorities, indicating a sub-optimal detector location.

For the remaining locations the Bluetooth detection rate can be determined by the quotient of the filtered detected individual vehicles with an entrained Bluetooth device and the traffic volumes detected by the ground truth inductive loops of the BASt.

Filtered in this case means for example the elimination of multiple devices on board of the same vehicle. Hereby, the term multiple devices is defined as the situation that one individual vehicle is carrying several devices with activated Bluetooth interface simultaneously. To not bias the determined detection rates these situations have to be filtered because all those devices actually represent the same vehicle.

To achieve that, the TUM-AID algorithm compares the temporal offset of the detection of two or more directly consecutively detected MAC addresses at successive detector locations. If also at successive detectors those offsets are temporally close to each other, it can be assumed that the devices are on board of the same vehicle. The approach is also shown in the following figure 4.

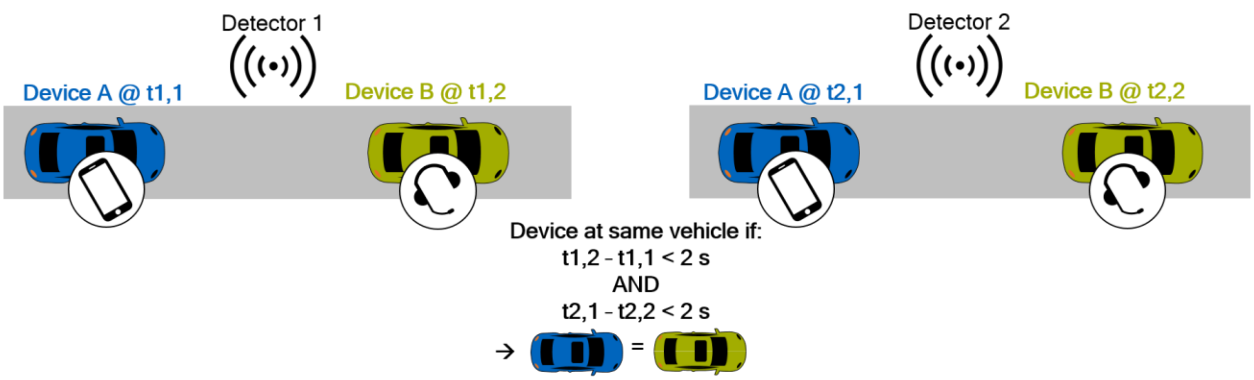

FIGURE 4 Principle of the detection of multiple devices on board of one single vehicle.

In figure 4 a situation is shown, where the first detector detects two individual devices, which leads to the assumption that two vehicles (marked here as blue and green) have passed the detector. The same two devices are afterwards also detected at a subsequent downstream detector. The algorithm now checks if the time gap between both detections at detector 1 is small. If the time gap between the detection of both devices at detector 2 is also small, this is an indicator that both devices are actually inside the same vehicle.

This applies to approximately 15 % of all detected MAC addresses which means that on average every sixth vehicle carries two instead of just one Bluetooth device. For the calculation of the Bluetooth detection rate as well as for the further calculation of additional traffic parameters these secondary devices are filtered in order to minimize the falsification of the sample.

In total, after applying the above mentioned method, the Bluetooth detection rates were determined over a period of seven years from 2010 to 2016 (2009 was excluded because there was still the trial phase with very few detections, 2017 was excluded because the ground truth was not yet available). Altogether 18 Bluetooth detector locations fulfilled the requirements mentioned above, distributed across the entire North Bavarian freeway network.

RESULTS

An exemplary result for the Bluetooth detector 4108 at the freeway A3 is shown in the following figure 5. The blue continuous line shows the Bluetooth detection rate which was determined using the traffic volumes from the adjacent loop detector 9038 as a ground truth. The dashed blue line represents the moving average of the detection rate. Since the detection rate is largely influenced by the share of trucks this parameter is also shown by the continuous red line.

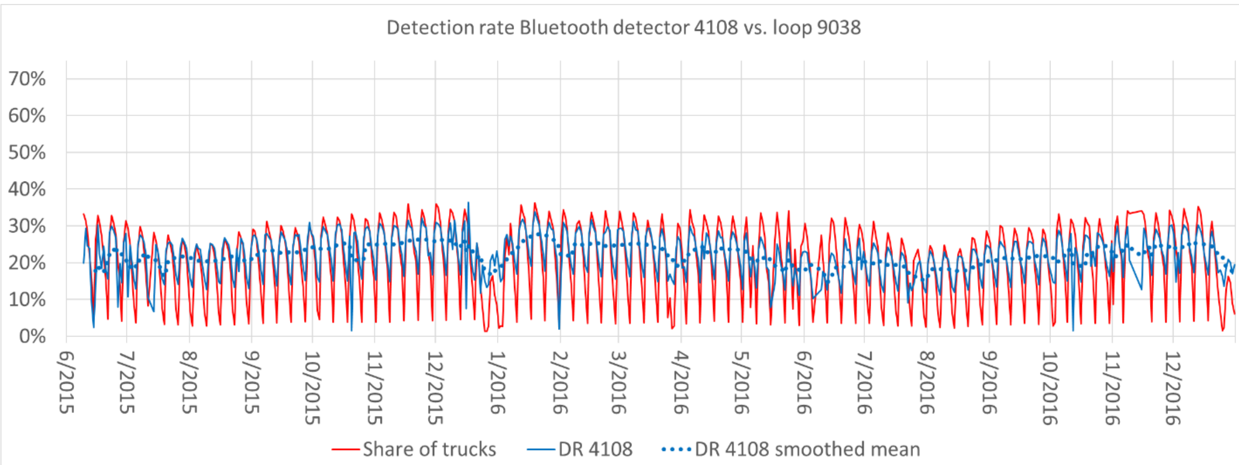

FIGURE 5 Detection rate Bluetooth detector 4108 vs inductive loop 9038 at freeway A3.

The detection rate amongst trucks ranges between 65 to 70 %, which means, that they are approximately five times more often equipped with an active Bluetooth device than passenger cars (detection rate around 12 to 17 %). A correlation between those two parameters is clearly recognizable in figure 5. The detection rate in blue follows the truck share in red in a weekly pattern in the form of a decrease in the detection rate at the weekends. This is due to generally less commercial traffic on the weekends but also the truck-driving ban on German freeways on Sundays and bank holidays from 0:00 to 22:00. Also visible are periods with missing data but also the decline in detection rate around Christmas and New Year caused again by the lower proportion of trucks at these days. A significant negative impact of the influence of the truck share on detection quality at weekends is not noticeable as the rate is still high enough for most applications.

Also a seasonal effect during public holidays especially the six weeks long public summer holidays in Bavaria is visible. During this holiday period, which is normally between end of July to mid of September, the detection rates on almost all evaluated locations are slightly dropping. The reason for that is probably the reduced amount of business traffic and commuter during these days.

The following graphs (figure 6 through figure 11) show several other selected measurement locations at different freeways for different time intervals. It can be seen that especially in the earlier years from 2011 to 2013 the graphs show some gaps, where either the Bluetooth detector, the loops for comparison or the Bluetooth data collector was not working. It can be observed that there are several peaks in the detection rate where in some cases the loops delivered lower traffic volumes or the Bluetooth detectors had a high increase in detections.

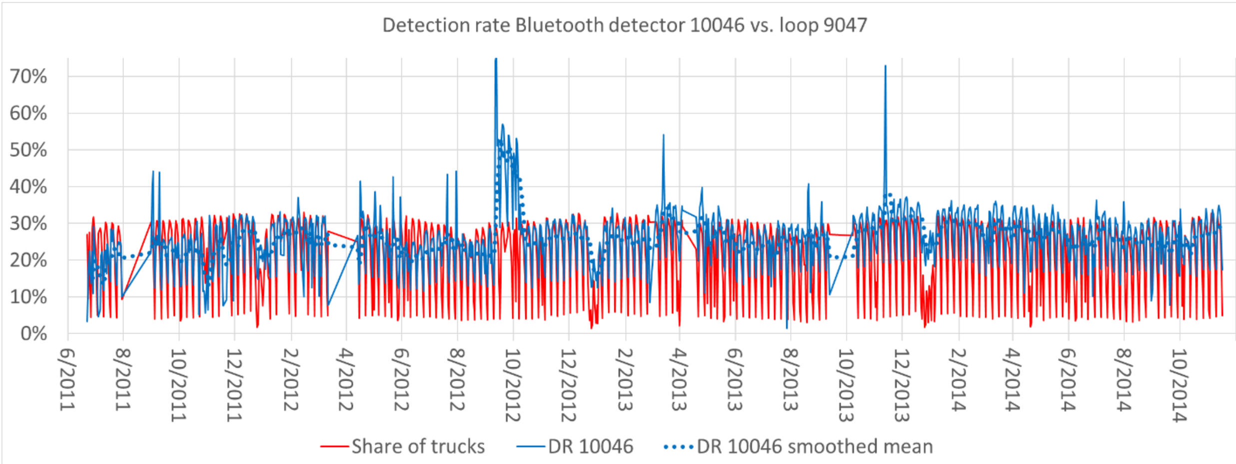

FIGURE 6 Detection rate Bluetooth detector 10046 vs inductive loop 9047 at freeway A6.

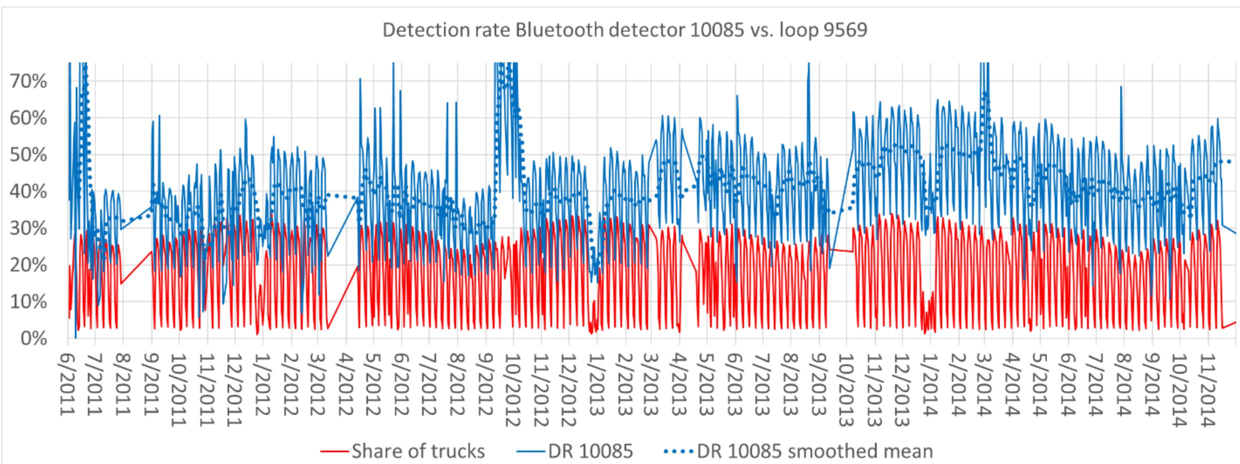

FIGURE 7 Detection rate Bluetooth detector 10085 vs inductive loop 9569 at freeway A7.

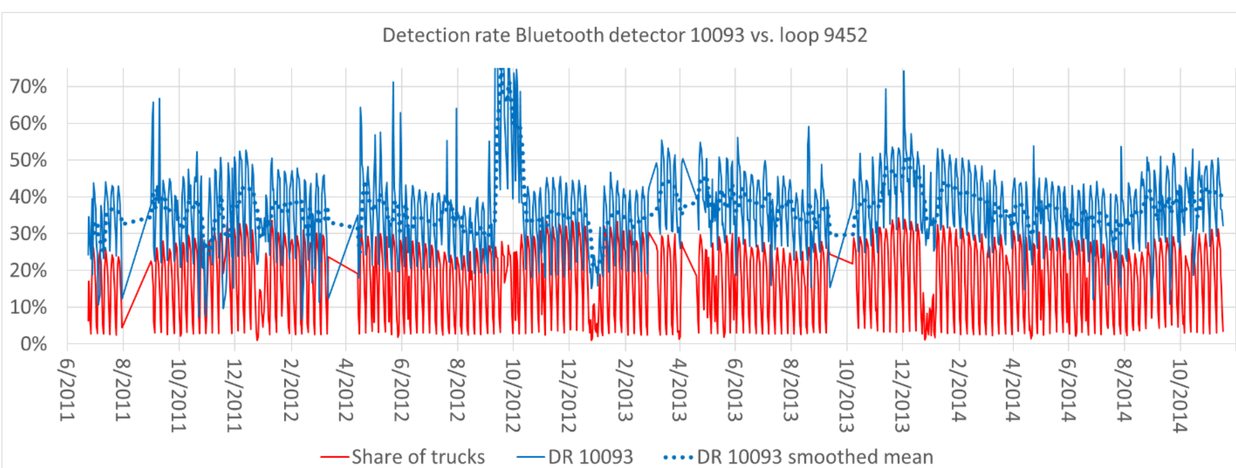

FIGURE 8 Detection rate Bluetooth detector 10093 vs inductive loop 9452 at freeway A7.

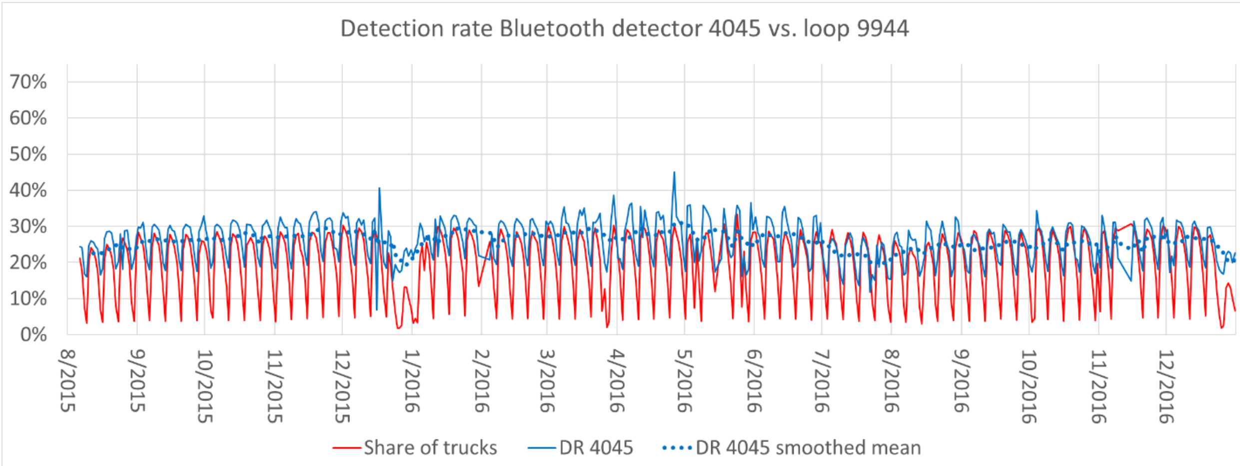

FIGURE 9 Detection rate Bluetooth detector 4045 vs inductive loop 9944 at freeway A6.

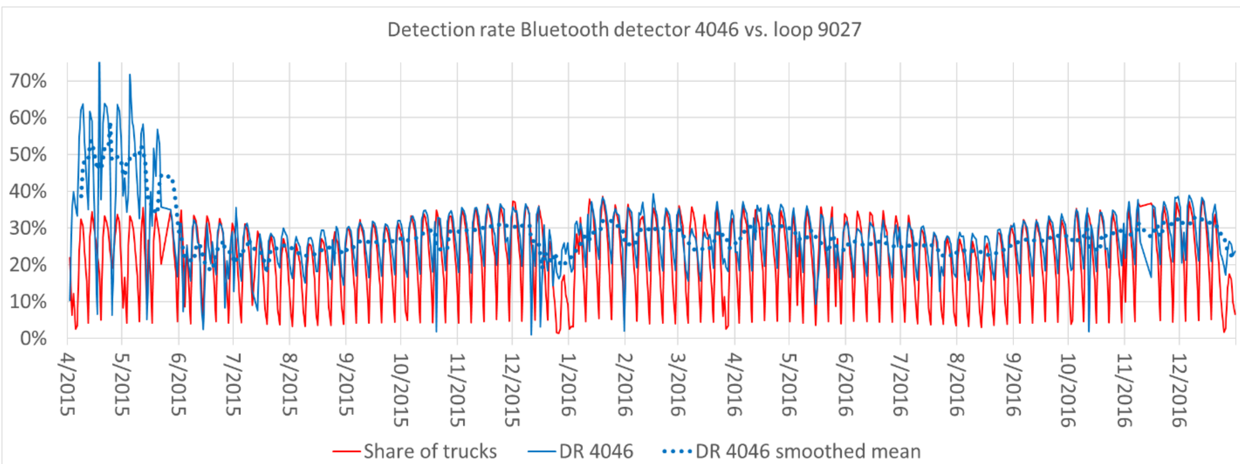

FIGURE 10 Detection rate Bluetooth detector 4046 vs inductive loop 9027 at freeway A3.

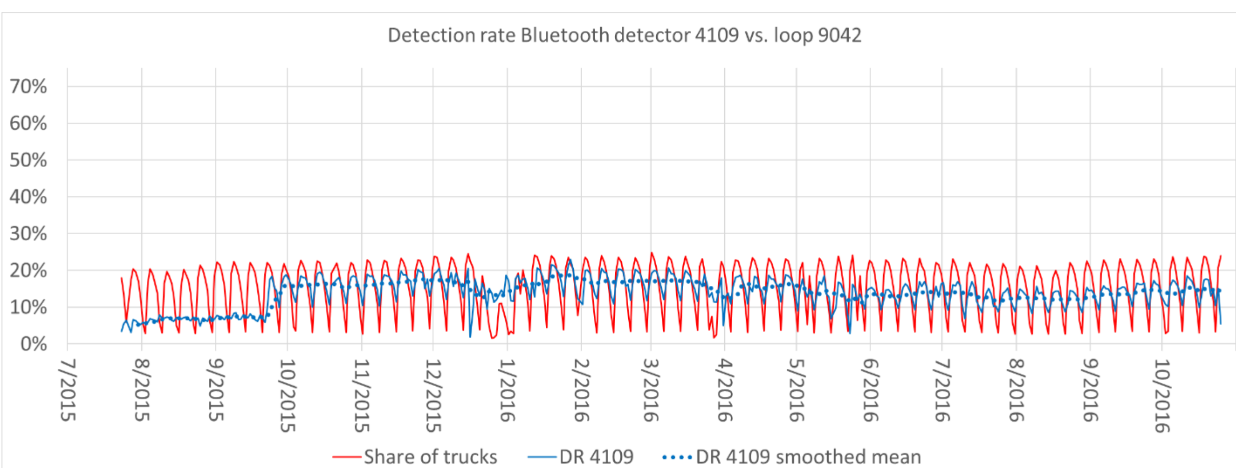

FIGURE 11 Detection rate Bluetooth detector 4109 vs inductive loop 9042 at freeway A9.

After evaluating a total of 12,677 measurement days (in average around 700 for each combination of Bluetooth detector and inductive loop) it can be stated that the detection rate averages 23.8 % on the observed detector sites. Since not all sites cover a similar amount of measurement days the individual sites were weighted according to their duration of the respective measurement period. This leads to a weighted average detection rate of 25.6 %. It is important to note that this average value remains constant over the observed years and no trend can be seen for a decrease or an increase in the detection rate in Northern Bavaria. The following table 2 summarizes the mean detection rates of all tested Bluetooth detector sites. The evaluated detectors were installed for different time periods.

TABLE 2 Overview over detection rates at several detector locations.

Measurement years	Measurement days	Freeway	Location	Detection rate
2010	55	A7	AK Feuchtw/Crailsh (N)	20.7 %
2011 – 2014	1380	A3	AK Nürnberg (W)	21.2 %
2011 – 2014	1244	A6	AK Nürnberg-Ost (W)	22.0 %
2011 – 2014	1244	A7	AK Biebelried (S)	31.5 %
2011 – 2014	1380	A7	AK Feuchtw/Crailsh (N)	34.6 %
2011 – 2014	1380	A7	Bottenweiler	35.3 %
2014 – 2015	261	A3	AK Nürnberg (W)	24.7 %
2015 – 2016	633	A3	AD Seligenstadt (O)	20.5 %
2015 – 2016	571	A3	AK Biebelried (O)	18.8 %
2015 – 2016	639	A3	Kitzingen/Schwarzach (O)	23.9 %
2015 – 2016	514	A6	AK Nürnberg-Süd (W)	22.0 %
2015 – 2016	569	A7	AK Feuchtw/Crailsh (N)	26.9 %
2015 – 2016	624	A7	AS Wasserlosen	26.8 %
2015 – 2016	569	A7	Bottenweiler	26.6 %
2015 – 2016	527	A9	AK Nürnberg (N)	11.7 %
2015 – 2016	527	A73	Röthenbach	18.5 %
2016	243	A7	AK Biebelried (N)	22.6 %
2016	317	A7	AK Feuchtw/Crailsh (S)	19.8 %
Mean detection rate:				**23.8 %**
Mean detection rate weighted by amount of measurement days:				**25.6 %**

In general, it should be noted that the main influence on the observed differences in the detection rates across the different locations is probably due to the surroundings of the location and the installation height and orientation of the antenna.

In addition, it should be mentioned that the Bluetooth detection rates are independent of the distance between succeeding Bluetooth scanners as they are determined purely locally at individual detection sites. The resulting matching rates (defined as the number of Bluetooth devices recognized on a route between two detectors in relation to the prevailing total traffic volume) are also independent of the distance between the detectors.

It is only relevant which proportion of the vehicle collective has left the freeway between the two observed detectors (e.g. via freeway interchange, on- and off-ramps, freeway resting areas etc.). There is a direct linear relationship between the proportion of vehicles driving off and the resulting reduced matching rate. If for example 30 % of the vehicles leave the freeway after passing the first Bluetooth detector location and thus do not reach the second detector location, then a 30 % lower matching rate will also occur between the two detectors respectively.

Coming back to the detection rates which have shown to be very steady throughout the years. For the next few years, no opposite trend can be expected. On the one hand, this assessment is based on the fact that Bluetooth interfaces continue to be an integral part of in-vehicle entertainment and communication systems. According to (22), 86 million, representing a share of 86 % of all new sold cars are equipped with a Bluetooth interface in 2018. Additionally, also in mobile electronic devices (e.g. due to the trend towards wireless Bluetooth headphones), Bluetooth remains the unrivaled wireless standard for the connection of peripheral devices. The Bluetooth Special Interest Group (22) states that only in the year 2018 four billion devices with a Bluetooth chip will be shipped including more than one billion wearables or devices for audio streaming and more than 1.5 billion smartphones.

However, even for the unexpected case of the decline in the number of Bluetooth devices, the automotive 802.11p WLAN standard ITS G5 offers an alternative radio technology, which is equally suitable for the generation of equivalent traffic data.

CONCLUSIONS

It can be concluded that on a weighted average over the years 2010 to 2016 the detection rate of the detector locations in Northern Bavarian was 25.6 %. The Bluetooth detection rate has been quite constant over the past eight years and no contrary trend is expected for the coming years.

Existing literature shows a huge variety of realized detection rates ranging between 0.2 % and up to 70 % with in average around 15 %. Additionally, a difference between the average detection rates at European test sites and the U.S. can be observed. In the available data for European countries the Bluetooth detection rate was approximately 30 % whereas in the U.S. only around 6 % were be observed.

One outcome of the analysis of the detection rate on German freeways was that the equipment rate with Bluetooth devices amongst trucks is partly five times higher than the one from passenger cars. Therefore, also the detection rates amongst heavy traffic are higher (share 65 % to 70 %) in comparison to cars (share 12 % to 17 %). This data characteristic has to be taken into account when using the Bluetooth data for further determination of traffic parameters since trucks will have for example a higher impact on the travel time evaluation based on Bluetooth detections.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: Data analysis, method development and interpretation of results: Martin Margreiter. General study conception and design, draft manuscript preparation: Fritz Busch. Data collection and provision, advice on traffic data: Christian Carstensen. All authors reviewed the results and approved the final version of the manuscript.

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