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Evaluation of Stationary, Link-based and Floating Vehicle Data for Estimating Travel Times on Freeways

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Abstract

Travel time measurements are an important indicator for evaluating traffic flow conditions or the effectiveness of various traffic management and control measures and thus their accuracy is of great importance. This paper compares travel time measurements from four different data sources including Floating Vehicle Data (FVD), local detectors, CONSYST data and Bluetooth re-identification. The different data sources are evaluated depending on their penetration (for FVD and Bluetooth) and detection (for inductive loops) rates, the vehicle composition as well as their travel time values on different days. Travel time values are compared for days with and without an incident occurrence separately, as the traffic evolution significantly differs. Firstly, data source characteristics are identified based on the observation of travel time plots and differences and similarities are further assessed and estimated via statistical analysis and pairwise comparison. Finally, a statistical analysis and pairwise comparison are conducted to determine the travel time correlations between all data sources on different days and under various traffic conditions.

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Keywords: Floating Vehicle Data; Travel Time; Local Detectors; Bivariate Correlation

1. Introduction

Travel time values are an important indicator taken into consideration for applying changes in the infrastructure or the traffic management and control strategies. Real time measurements are the basis for advanced traveler information systems that provide information to the users in order to assist them in making various decisions, such as route choice or making a detour in case of congestion. Due to the increasing problem of traffic congestion, it is of vital importance to provide accurate travel time measurements, thus to define the most precise method for their estimation. Since travel time measurements have complex data requirements and require high data accuracy, their estimation has been a core point of research and various technologies have been

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developed and used such as GPS-equipped probe vehicle (Hunter et al., 2006), transit buses and automatic vehicle location (Bertini and Tantiyanugulchai (2003), Lin (2009)), Floating Vehicle Data (FVD) (De Fabritiis et al. (2008), Kerner et al. (2005)) and extended Floating Vehicle Data (xFVD) (Huber et al., 2005). On the other hand, Sun et al. (2004) and Volling (2009) proposed a multi-detector fusion method for calculating travel times on freeways by matching the magnetic signatures of vehicles at two different points on a roadway while radio-frequency identification (RFID) toll tag technology has been used to record travel times (Wojtowicz et al. (2008)). The use of Bluetooth data for estimating travel times is also widely used in literature (Tarnoff et al. (2009), Puckett and Vickich (2010), Haghani et al. (2010), Haseman et al. (2009), Araghi et al. (2012)) while in Margreiter (2016a, 2016b) Bluetooth technology is applied for the detection of unexpected events such as accidents based on travel time changes. Except of the different methods for obtaining travel times, research is also rich in comparing the different methods. Bar-Gera (2007) revealed a good match between cellular phone-based system, dual loop detectors and FVD even though there is a constant bias of about one minute between the travel times computed from the cellular phone and loop detector data, especially during uncongested times. Bluetooth technology was found to provide accurate travel time measurements under homogenous traffic conditions (PennDOT (2010), Malinovskiy et al. (2010)), to agree with GPS data on non-congested conditions (Saunier and Morency (2011)). Vo (2011) evaluated the accuracy of Bluetooth devices and proved that they could estimate travel times with high accuracy but compared to the GPS measurements the values were smaller. Liu et al. (2012) showed that compared to the FVD, the speed estimation with the Bluetooth data is closer to the Co-Pilot data, FVD are underestimating the speed, while TRANSMIT and Bluetooth data are closer to ground truth and have higher accuracy and reliability than FVD. Finally, the analysis performed by Jia et al. (2013) showed that the FVD travel times appeared to approximate a little closer to the ones derived from video-based data.

The present paper extends past research by comparing four different methods for obtaining traffic data and estimating travel times. These methods are based on different types of detectors, stationary, link-based and floating vehicle data and are the following: (a) FVD, (b) virtual travel time data provided by CONSYST, (c) re-identification of vehicles via Bluetooth sensors and (d) local detection via inductive loops. The analysis will provide positive and negative characteristics of each data source by comparing not only travel time values but also other parameters. Travel time trends will be analyzed and compared based on the type of day, the time period within the day as well as accident occurrence detection based on travel time changes. Past research will be further extended by determining the relevant sample size for each detector as well as the penetration rate in the overall traffic. For each data source, the input composition of vehicle types within the data samples will be analyzed in order to determine the effect on the quality of the data source and possible distortions with the extrapolation on the overall traffic. Furthermore, the different techniques will be compared qualitatively, based on plots and travel time values observation as well as quantitatively through statistical analysis while the analyses will be divided in days with and without incident occurrence. All the above aspects will give a better overview and explain more explicitly the behavior of each dataset.

2. Study Area and Database

The study area is located at the freeway A3 in Germany, a freeway that links the border with the Netherlands near Wesel in the northwest to the Austrian border near Passau in the southeast. The A3 is a major connection between the high-density Rhine-Ruhr area and southern Germany, resulting in heavy traffic. Consequently, large segments have three lanes (plus hard shoulder) in each direction. The analyzed part of this work is located between Erlangen-West and Neumarkt with a total length of 579 km (Fig. 1). As already mentioned, the available dataset consists of data collected from four different sources. The FVD database consists of speed data recorded for 42 days from 2012-10-01 until 2012-11-11. The data is aggregated per minute and besides the actual speed, historical speed values and free flow speed values for each minute are provided. CONSYST data is obtained from inductive loops located on the freeway. The model behind the CONSYST data is the ASM model developed by Treiber and Helbing (2002). It is a method for obtaining spatiotemporal information from aggregated data of stationary detectors having heuristically motivated properties. The model results in obtaining velocity, flow and other traffic variables as smooth functions of space and time and it filters out small scale fluctuations and has been used in different applications (Schreiter et al. (2010), Treiber and Kesting (2010), Van Lint (2010)). The CONSYST dataset consists of travel time data for the same period and is aggregated every five minutes. 33 inductive loops, located in different positions along the study area in both directions, recorded speed data per minute, used for this analysis. For safety reasons and because it is unclear which detectors are more important for the speed calculation the weights among the detectors are equal for calculating the average speed. The last source for data acquisition are Bluetooth sensors, installed at the roadside of the freeway, collecting travel times of passing vehicles equipped with Bluetooth devices. The Bluetooth dataset contains travel time and speed measurements in two different segments (a longer and a shorter one) per direction and per minute and are defined by the three Bluetooth stations located along the study area. Because of the high number of missing values and the fact that it is not safe enough to convert five-minute to one-minute data, it was decided to aggregate the data of FVD, Bluetooth and local detectors to five-minute data.

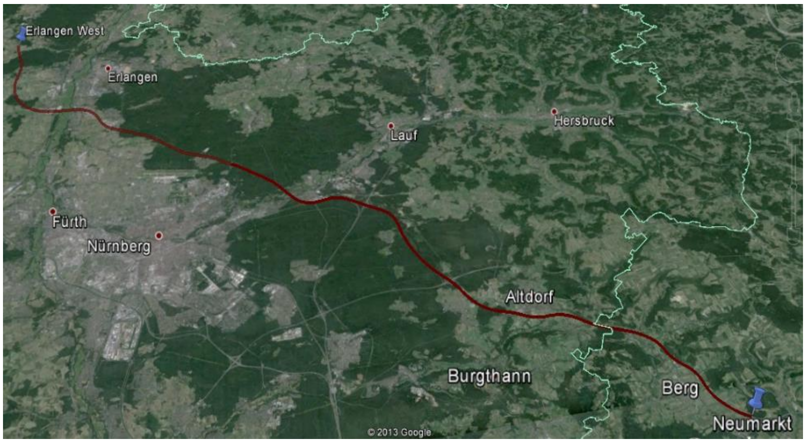

Fig. 1. The study area between Erlangen (West) and Neumarkt at the German freeway A3 close to Nuremberg.

3. Comparison of Penetration Rate and Vehicle Composition

The calculation of the penetration rate requires information of the total number of vehicles. Due to the fact that this kind of information is not provided, it is assumed that the local detectors can provide approximately the daily number of vehicles driving across the freeway. For this purpose, the number of vehicles for each segment, based on the number of vehicles detected by the first and the last local detector of each segment was calculated. For calculating the penetration rate, the number of FVD vehicles or vehicles equipped with Bluetooth devices is necessary to be defined. The Bluetooth dataset provides itself the total number of cars per segment and direction from additional inductive loops while the estimation of the number of FVD vehicles was based on the speed differences within the day. More specifically, for each sub segment it was assumed, that when there is a speed difference between the previous and the next minute a new car enters the sub segment. By counting the number of speed differences, the number of cars per day within a sub segment is calculated. The results showed that the minimum penetration rate of the FVD is 0.73%, the maximum 2.47% while 1.55% and 1.43% are the average penetration rates for south and north direction respectively. The Bluetooth dataset analysis gives a minimum penetration rate of 3.24%, while the highest one is around 17.46%. The average penetration rates per direction are much higher than the FVD penetration rates; 11.79% for the north and 7.48% for the south direction. The first impression occurring from the above results is that Bluetooth might provide a better and more accurate traffic information than FVD as more signals are recorded and more vehicles are moving in the traffic delivering data. It should be mentioned that Bluetooth penetration rates might be higher than the actual values because the dataset gives the number of vehicles detected according to the devices detected. This means that in the case that two or more devices within one vehicle are activated giving a Bluetooth signal to the stations, two or more vehicles passing are recorded instead of one. As a result, there is a possibility that the real number of vehicles is slightly different. In order to overcome the issue of vehicle number miscalculation in case of Bluetooth data, the segments were the penetration rates differed significantly were omitted from the analysis.

A significant factor affecting data quality is the vehicle composition, represented by different types of vehicles driving on the road segments and their percentages. Only two vehicle categories are distinguished here: passenger cars and trucks. The vehicle composition influences the traffic information recorded and sent to the main center as trucks have lower speeds and as a result increased travel times influencing also the average travel time. Loop detectors have the ability to distinguish different vehicle types based on their inductive signature. The available dataset provides the number of passenger cars and trucks passing the local detectors. An analysis of the available dataset shows that the lowest percentages of trucks occur during the weekends, especially on Sundays. More specifically during weekdays, the mean percentage of trucks using the freeway is around 25% for all segments. On the other hand, during the weekends, the average proportion of trucks is around 10% and only for Sundays it is around 5%. The above vehicle composition explains the fact, that when plotting the travel times calculated from the local detector's recorded speeds, the values appear to be low. As far as the Bluetooth dataset is concerned, the characterization of a vehicle as a truck is based on a very simple algorithm: when the speed of the vehicle detected by the Bluetooth sensor is lower than 100 km/h, it is considered to be a truck, otherwise it is considered to be a passenger car. Since there are cars driving in lower speeds, it is important to mention that this simple algorithm cannot give the actual number of cars and trucks but an under- and overestimation respectively. It will be used as a rough estimation of the number of trucks and cars, though. The method gives a higher proportion of trucks compared to the ones given in the local detector dataset and the speed of the trucks calculated from local detectors is always higher than the corresponding speed obtained by the Bluetooth dataset. Therefore, it is expected that the travel times recorded by Bluetooth sensors should be higher than the values obtained from the local detector dataset due to the higher presence of trucks and due to the fact that most of data is obtained by trucks (Fig. 2). Since the difference in the vehicle composition of the different data sources was not significant, no further adjustment was necessary to be applied.

4. Comparison of the Different Data Sources: Qualitative Analysis

Due to the fact that no real ground truth data was available, the analysis was conducted by comparing the data collection methods among each other. The first step is a qualitative analysis, by observing the trends of the travel time evolution within each day and for each segment and taking into consideration the characteristics of each source. Moreover, the datasets will be compared in pairs through a more detailed qualitative analysis and differences between stationary and link-based detectors will also be revealed. The analysis is divided in two parts: days with an incident occurrence and days without an unexpected event.

4.1. Days with no Incident Occurrence

All the plots, without exception, illustrate the same fact: the travel times calculated by using local detectors data are the lowest among all the data sources, mainly due to the position of successive stationary detectors and their distance between. The distances between successive detectors range from 0.3 km up to 6.1 km, meaning that some of them are significantly away from each other. The conditions for each segment are defined by the data recorded in the local detectors located at its begin and its end without having any other information. When the local detectors are in such a high distance from each other, then the speed values obtained may not depict the real traffic conditions within the segment. Compared to the other sources (Bluetooth and FVD), where the data is obtained for much smaller segments or speed data is recorded for intervals less than a minute, it is obvious that local detectors cannot track any changes in traffic conditions especially when its spatiotemporal influence is very small. Additionally, Bluetooth gives directly the travel time by detecting the same vehicle on the successive Bluetooth station, meaning that the method tracks the changes in traffic conditions more efficiently than local detectors. Bluetooth travel times are higher than the local detector values as well as the FVD time values especially during the weekdays and the early morning period until approximately 8:00. As it has already been mentioned, this is due to the fact that Bluetooth data is mainly obtained from trucks and truck drivers mainly drive from 22:00 or 23:00 till 8:00 in the morning. During the rest of the day and during weekends and holidays, the Bluetooth values are again higher, but they differ in a smaller percentage from the other datasets due to the lower number of trucks. Additionally, Bluetooth values present higher fluctuations and spread than the other datasets, maybe due to the fact that within the dataset there are some unreasonable low values. It is interesting, that during the early morning period CONSYST data presents also high travel time values, which are very close to Bluetooth values. Another observation, which derives from the plots is, that CONSYST data gives higher travel time values than local detector data despite the fact that the same data is used. Sometimes it appears that the two data sources follow different trends within the same day (early in morning and late at night) as shown in Figure 2. In the period between, they follow same trends. The difference between CONSYST and stationary detector travel time values is observed also on Saturdays but not in the same frequency as during weekdays. Furthermore, it is important to highlight that the differences in travel time evolution between CONSYST and local detectors data are more often observed in the bigger segments in both directions. For the smaller segments, differences were mainly observed in the values and not in the trends.

Figure 2 illustrates the differences between CONSYST and local detector data as well as the similarities between Bluetooth and CONSYST data during the early morning. During the late evening or night period when CONSYST and local detector data diverge again, the travel time values estimated using CONSYST data is closer to the values and trends of Bluetooth and FVD. The periods early in the morning as well as the periods from late evening until night were analyzed and observed through the above figures. As far as the period between is concerned the figures above indicate that all data sources do not significantly diverge and thus their values are close to each other. A common conclusion cannot be drawn and thus a further analysis is conducted in the next part (qualitative analysis) where the data sources are compared more thoroughly. Taking into consideration, that the above period includes also the two peak hours (morning and evening peak) a qualitative analysis is necessary for a better and more detailed comparison and evaluation of the data sources during this time. A closer look to the data and the plots reveals that FVD is the data source with the most intensive fluctuations and the data follows a trend of successive reduction-increases and peaks. Bluetooth may be the source with a broader range of values (bigger spread) while the smoothest trends are performed by stationary detectors and especially by CONSYST. This fact can be attributed to the model used behind the CONSYST model that is smoothing small-scale fluctuations of the data recorded by the local detectors. Fig. 3 shows a typical day and depicts each data source separately and the big spread of Bluetooth data.

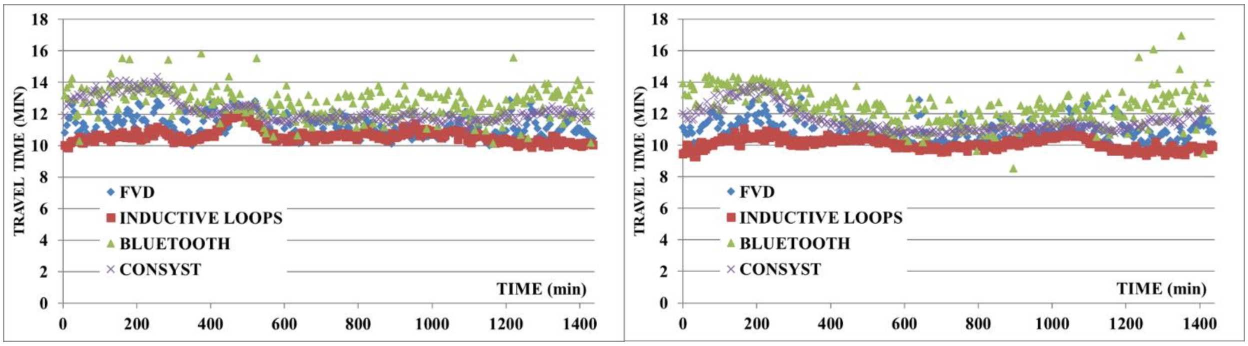

Fig. 2. Travel times on a weekday in the segment (a) southbound direction (b) northbound direction.

4.2. Days with Incident Occurrence

Days when an incident has occurred are analyzed separately in order to reveal how the data sources behave in such conditions. The parameters that were analyzed were the incident duration, the earliest and latest response, the earliest and latest dissipation as well as the peak values. Totally 30 incidents were analyzed for both segments and directions. The comparison showed that Bluetooth or CONSYST data are the data sources with the most often observed earliest response as well as with the earliest dissipation. On the other hand, FVD is the data source that mainly recognizes the changes in the prevailing traffic conditions later than the other sources and also performs the latest dissipation. Therefore, this shows that FVD does not assess similarly with the other data sources the congested conditions, caused by the incident occurrence, and that there is a transposition of the curve to the right.

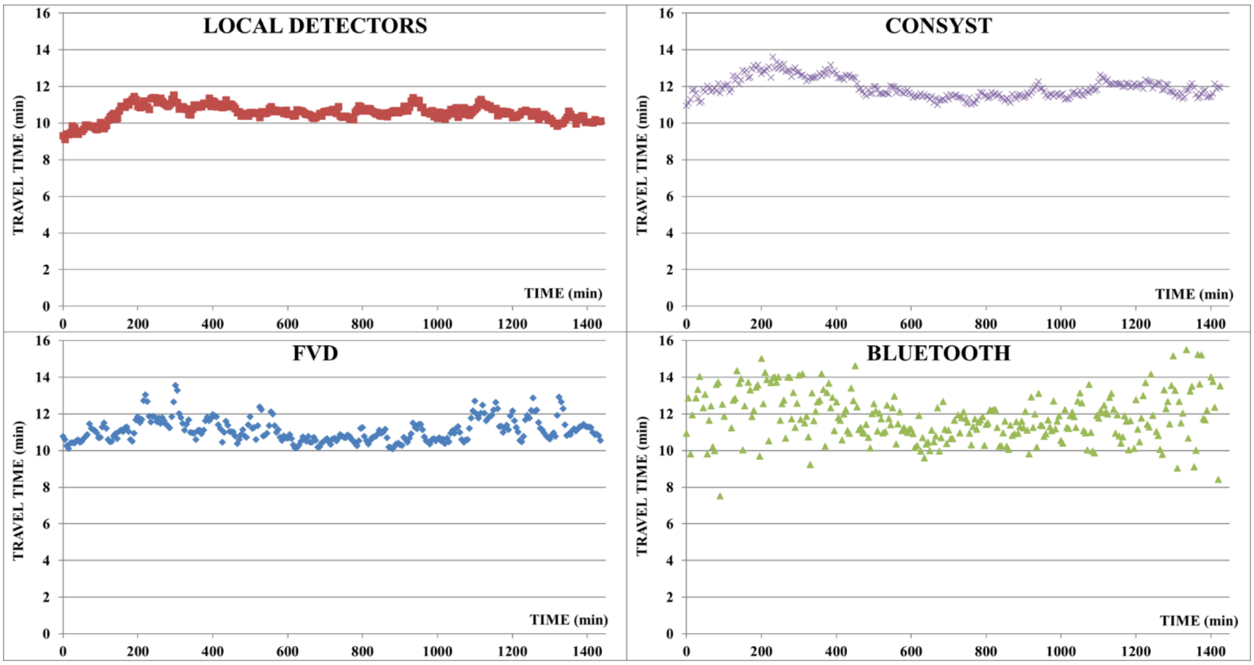

Fig. 3. Separate plotting of each data source for a typical weekday.

One of the most important observations is the different maximum travel time values during the congestion. The data sources present high deviations in the maximum travel time increase due to an incident (in some cases the difference was 30 minutes). The most frequent high values are performed by Bluetooth or FVD while the lowest values were determined mainly by CONSYST and local detectors. This may be reasonable if the way each data is collected, is considered. Bluetooth technology measures travel time by detecting the same vehicle in two successive Bluetooth stations, meaning that the movement of the vehicle through the segment is affected by the prevailing traffic conditions and thus the time to reach the next Bluetooth sensor. FVD technology receives signals from vehicles moving through the traffic and the defined segments are smaller than the defined segments by the stationary detectors. On the other hand, local detectors record speeds from vehicles passing and the section speed derives from the average between the speeds recorded by two successive stationary detectors. Therefore, local detector data could illustrate the congestion phenomenon resulted by an incident occurrence but the magnitude of its impact on traffic and travel times could not be correctly illustrated.

5. Comparison of the Different Data Sources: Quantitative Analysis

In this part a deeper analysis is conducted by comparing the data sources per pair and then according to the type of detector (stationary, link-based). The analysis divides again in two parts: days with and without incident occurrence.

5.1. Days with no Incident Occurrence

For conducting the analysis bivariate correlation is used, showing the correlation between each pair of the data sources. The significance level is set equal to 95 % (p value = 0.05), as it is the most commonly and widely used. A significance level equal to 95 % shows that there is a probability of 95 % that the result is true (or a probability of 5 % that the findings are not true). Two samples were used: one for observing the correlation during the week and one for applying correlation during weekends. As far as the week sample is concerned, it is known that on Mondays and Fridays traffic conditions are different than during the other three working days of the week and thus it seems reasonable to exclude them from the analysis. Furthermore, the data availability was high during three weeks out of the six available and thus the sample for the weekdays consists of three Tuesdays, Wednesdays and Thursdays. Table 1 shows the pair correlation results and indicates that the highest observed correlation is between CONSYST and Bluetooth data (r = 0.500), something that was also observed in the previous analysis. Correlation between FVD and CONSYST and between local detectors and CONSYST is almost equal and very low, something that was also indicated during the qualitative analysis. It is interesting that the correlation between Bluetooth and FVD, the two link-based detectors, has the lowest value (r = 0.181). It is also important to mention, that for the typical weekday the correlation between CONSYST and the link-based detectors is higher than the correlation between local detectors and these data sources. According to the observations in the qualitative analysis, the results are showing, that during a whole weekday Bluetooth and CONSYST data seem to be closer to each other (especially in the early morning period and late at night) and that CONSYST data is closer to FVD and Bluetooth than the local detector data to the same data sources. The same correlation coefficients are observed for each of the three weekdays (Table 1). It is observed that on Thursdays the data sources are better correlated compared to other weekdays, maybe due to the higher volumes that were recorded on that days. Making the analysis deeper, correlation was checked also during the peak hours: morning peak (7:00 – 10:00) and evening peak (16:00 – 19:00) according to the travel time values (Table 1). The results indicate that the highest correlation is between local detectors and CONSYST data while all the other calculated correlations are very low. In some cases, the significance level was higher than the p value (= 0.05), which means that there is no relationship between these data. Concerning evening peak, the highest correlation is again between CONSYST and detector data and the second highest between FVD and local detectors. It is interesting, that the Bluetooth data have the lowest correlation with all the other data sources maybe to the high percentage of trucks. However, during the peak periods the correlation is very low. If the whole day is considered then as plots indicate, Bluetooth and CONSYST data have closer travel time values and trends during the early morning hours but after that time they differ. That is also the reason why their correlation during the whole day is low. All the above results agree with the previous qualitative analysis that showed, that during weekdays the data sources are getting closer after the early morning period and before the period late at night and thus CONSYST and local detector data present the highest correlation during the peak hours. Bluetooth and FVD because of the outlier's fluctuations and spread (Bluetooth especially) they present low correlation with the other data sources and among each other. Similarly to the sample determination for weekdays, the sample for weekends is also chosen depending on data availability and it was decided that the sample consists of three weekends (six days). Stationary detectors and CONSYST present the highest correlation (r = 0.687). The second highest correlation is between Bluetooth and CONSYST, showing that also during weekends the correlation between these two data sources is good. It is obvious that the coefficients for weekends are all higher than the values for the weekday analysis, a fact that maybe results in the high percentage of trucks during weekdays. The lowest value, also for this case, is the correlation coefficient between the two link-based detectors, FVD and Bluetooth. Statistical analysis also showed that during weekends correlation coefficients are higher for all pairs of data sources. This fact shows, that on the weekend data sources have closer values to each other and especially local detectors and CONSYST record similar travel time values compared to weekdays as it was observed in the qualitative analysis.

Table 1. Bivariate correlation for the three analyzed weekdays (significance < 0.05), for each of the analyzed weekdays (significance < 0.05) and during morning and evening peak.

Source		**FVD**			**Local Detectors**			**BLUETOOTH**			**CONSYST**	
FVD					0.282			0.181			0.360	
Local Detectors		0.282						0.245			0.382	
Bluetooth		0.181			0.245						0.500	
CONSYST		0.360			0.382			0.500				
DAY	Tue	Wed	Thu	Tue	Wed	Thu	Tue	Wed	Thu	Tue	Wed	Thu
FVD				0.146	0.240	0.418	0.201	0.140	0.202	0.293	0.353	0.413
Local Detectors	0.146	0.240	0.418				0.225	0.128	0.349	0.334	0.324	0.454
Bluetooth	0.201	0.140	0.202	0.225	0.128	0.349				0.504	0.450	0.543
CONSYST	0.293	0.293	0.413	0.334	0.324	0.454	0.504	0.450	0.543			

	Source	**FVD**	**Local Detectors**	**Bluetooth**	**CONSYST**
Morning Peak	FVD		0.279	Sig> 0.05	0.329
	Local Detectors	0.279		0.386	0.691
	Bluetooth	Sig> 0.05	0.386		0.334
	CONSYST	0.329	0.691	0.334	
Evening Peak	FVD		0.587	0.185	0.432
	Local Detectors	0.587		0.304	0.626
	Bluetooth	0.185	0.304		0.238
	CONSYST	0.432	0.626	0.238	

5.2. Days with Incident Occurrence

For analyzing the behavior of the different data sources during an incident occurrence, incidents with medium or high travel time increase were distinguished. These types of incidents present more interest, as the differences between the sources could be better identified than in cases where the incident caused a low increase in travel time values. For this category (ten incidents out of 26) the travel time increases up to twice the normal values and the temporal evolution is higher than one hour or even two hours. As the travel times are getting higher due to the incident occurrence and the temporal evolution also increases, the stationary detectors are more correlated to each other and their behavior is similar. This is also indicated by the statistical analysis which shows, that all correlation coefficients are higher than 0.5. More specifically the highest correlation is observed between Detectors and CONSYST data (r ~ 0.87) while the lowest one is between Bluetooth and FVD (r ~ 0.6). These results are in accordance with the qualitative analysis, which showed that in most cases Bluetooth and FVD were the first data responding to the incident and FVD the last dissipating. This lag may be the reason for this low correlation. On the other hand, local detectors and CONSYST were in most cases not the first or last data source responding in the incident and thus their behavior is closer to each other. The other correlation coefficients are between 0.7 and 0.8 with CONSYST data being closer to Bluetooth and local detectors closer to FVD. Two examples of this category are shown in the following Fig. 3(a). It is important to mention that the correlation results were not affected by the temporal influence of the incident. A very interesting case, which appeared only once in our database – but is worthy to be mentioned and further analyzed – is the case of two incidents occurring spatiotemporally close to each other. As the contour plot in Fig. 3(b) indicates the two incidents occur one after the other and probably it is a case of a secondary accident following a primary one. Literature has shown the significance of secondary incidents in traffic operations as well as methods for their detection (Orfanou et al. (2011), Vlahogianni et al. (2012), Imprialou et al. (2013)). The travel time evolution for this interesting case is depicted in Fig. 3(b). The plot showing the travel time evolution depicts the possible occurrence of two incidents as at the beginning travel time values significantly increase (up to 18 minutes), then they decrease and immediately they increase again up to 20 minutes. For this case the correlation analysis showed that all data sources respond well to these changes with the highest values of correlation being between local detectors and CONSYST and between FVD and stationary detectors (r ~ 0.9). The other correlations are around 0.7.

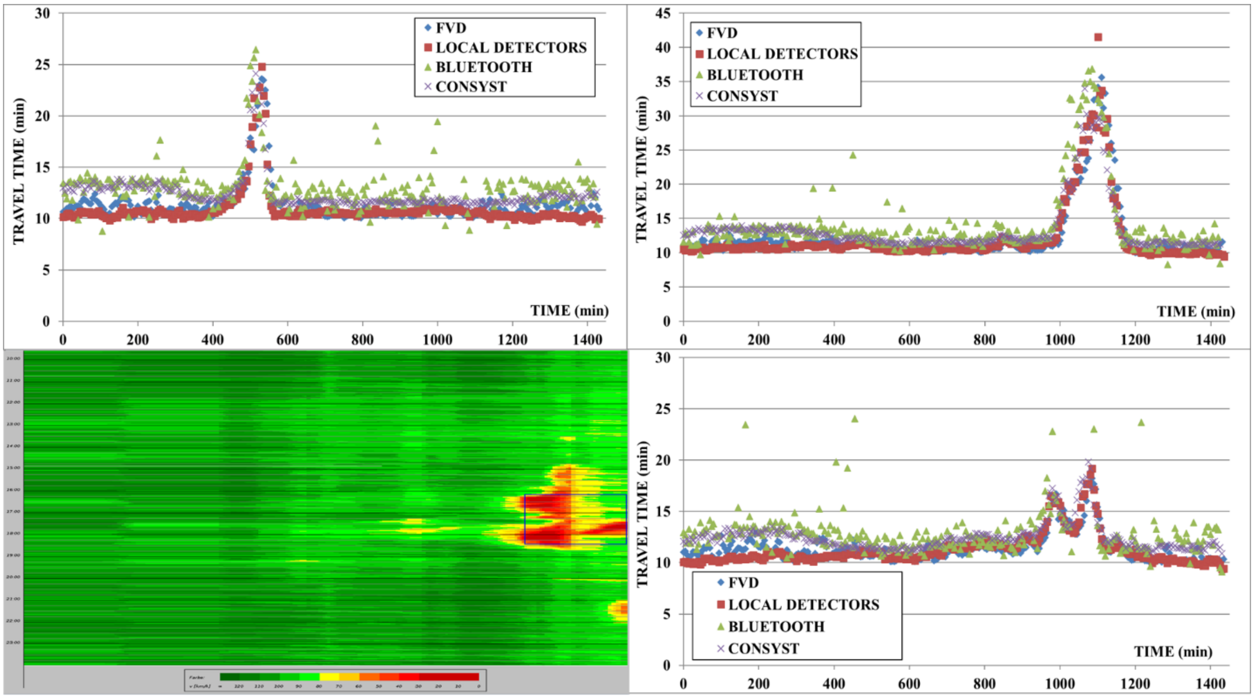

Fig. 4. (a) Travel time evolution for two incidents with high travel time increase (b) Contour plot showing the incident occurrence (CONSYST dataset) and travel time evolution for the case of a secondary accident occurrence.

6. Conclusion

This paper extends past research by comparing travel time measurements from four different sources including stationary and link-based detectors. The analysis of the trends and travel time values through plot observation, the bivariate correlation for different types of day and peaks along with the response of the sources in accident occurrence gives also an added value as it formulates a more complete comparison among the different sources. On average, Bluetooth and CONSYST data present similarities in values and trends during the whole day while the two link-based detectors present the highest deviation among each other. Narrowing down the analyzed time interval, it was revealed, that during the peak hours specifically, the two stationary detectors have the highest correlation but during the rest of the day they diverge. Analysis revealed that factors such as vehicle composition as well as length of the analyzed segments affect the characteristics of the different sources. In order to generalize the advantages and limitations of the analyzed methods, the comparison with ground truth data will be beneficiary for a better estimation of their accuracy and reliability on specific days and time periods as well as for a more efficient accident occurrence detection and prediction. Furthermore, a more advanced statistical analysis could reveal the influence of various parameters such as the day or the time of the day on travel time values while clustering techniques may result in travel time patterns that could be extracted from the database. Additionally, the comparison of the analyzed methods on a larger part of the selected freeway may give also give more precise results of the comparison among the analyzed techniques.

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