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ScienceDirect
Transportation Research Part C 15 (2007) 380–391
TRANSPORTATION RESEARCH PART C
www.elsevier.com/locate/trc

Evaluation of a cellular phone-based system for measurements of traffic speeds and travel times: A case study from Israel

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Received 12 February 2007; received in revised form 1 June 2007; accepted 4 June 2007

Abstract

The purpose of this paper is to examine the performance of a new operational system for measuring traffic speeds and travel times which is based on information from a cellular phone service provider. Cellular measurements are compared with those obtained by dual magnetic loop detectors. The comparison uses data for a busy 14 km freeway with 10 interchanges, in both directions, during January–March of 2005. The dataset contains 1284587 valid loop detector speed measurements and 440331 valid measurements from the cellular system, each measurement referring to a 5 min interval. During one week in this period, 25 floating car measurements were conducted as additional comparison observations. The analyses include visual, graphical, and statistical techniques; focusing in particular on comparisons of speed patterns in the time–space domain. The main finding is that there is a good match between the two measurement methods, indicating that the cellular phone-based system can be useful for various practical applications such as advanced traveler information systems and evaluating system performance for modeling and planning.

Keywords: Travel time measurement; Probe vehicles; Cellular phones

1. Introduction

Measurements of traffic speed and travel times are needed for a wide range of practical applications. Real time measurements are the basis for advanced traveler information systems (ATIS) that provide information to roadway users to help them in making various decisions, such as: route choice, departure time choice, etc. The information can be presented to travelers via variable message signs, internet websites, cellular phones, on-board navigation devices, and more. In addition, historical records of daily patterns of traffic speeds and travel times are highly needed in decision processes about investments in transportation infrastructure. When network-wide performance data will become available, it will enable major enhancements to

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0968-090X/$ - see front matter
doi:10.1016/j.trc.2007.06.003

transportation models, especially through better calibration and validation. Furthermore, on-going monitoring of system performance and their changes over time, both long-term trends and sudden changes, can improve our understanding of the causes and thus lead to better treatments.

The current state-of-the-practice for data collection regarding traffic speeds relies mainly on local detectors that measure the speed at a specific point along the roadway. One of the most widely used technologies for this purpose is magnetic loop detectors, installed under the roadway surface. Due to the cost of installation and maintenance of local detectors, they are typically installed only on a relatively small portion of the roadway system, thus providing limited coverage of the entire transportation network. In addition, in an urban environment there are many traffic interruptions, particularly at intersections. These interruptions cause delays that are not depicted by measuring speeds at any specific point along the road.

An alternative approach is to measure travel times of vehicles along a certain route or route segment. When a small number of occasional measurements are needed, dedicated ''floating vehicles'' can be used. Equipping floating vehicles with GPS can improve the accuracy of the measurements (Byon et al., 2006). A different approach (Boyce et al., 1994) is to use certain vehicles equipped with location and communication devices as ''probe'' vehicles, and to monitor their travel times as they perform their regular travel. The main issues in probe vehicle systems are location accuracy and coverage.

To examine the ability to meet location accuracy requirements, Yim and Cayford (2001) used a vehicle equipped with differential GPS (DGPS), and managed to match its route for 93% of the distance it traveled. Equipping vehicles with GPS are feasible mainly when considering specific fleets. For example: up-to-date travel time estimates for Berlin, Germany were obtained using 10 000 000 GPS observations from 300 taxis over five years (Reinhart and Schafer, 2006); link travel times were estimated from approximately 5 000 000 GPS observations at one second intervals collected by 12 GPS devices in a survey of 256 vehicles over 16 months (Du and Aultman-Hall, 2006); GPS equipped truck fleet was proposed as a means to evaluate infrastructure performance improvements (McCormack and Hallenbeck, 2005); and the potential of using location data of busses for estimating car travel times has been examined by Chakroborty and Kikuchi (2004). Data from a fleet of equipped vehicles, typically limited in its size, is also limited in its coverage, especially when real time data is needed. Furthermore, specific fleets often have specific travel patterns that are not necessarily representative of the entire population. Differences may be in the routes most often traveled, or in the speed of the fleet's vehicles compared with the general traffic.

To avoid equipment costs, either in the vehicles or along the road network, cellular phones can be used to identify locations, since any cellular service system contains information about the locations of its users over time. Cellular phones reached extensive market penetration in many countries. For example, in 2004 in Israel 83% of all households owned one cellular phone and 53% of all households owned two cellular phones or more; even in the lowest income decile 73% of the households owned one cellular phone and 28% of the households owned two cellular phones or more (Israeli Central Bureau of Statistics, 2006). Ygance (2001 cf. Yim, 2003) report that in a survey conducted in 2000 at the Rhone corridor, Lyon, France 77.4% of the automobiles had at least one cellular phone. Cayford and Yim (2006) showed that a cellular phone-based system producing data for 5-min intervals between 10:00 am and 10:00 pm covers on average 76% of 255 km freeways and 40–50% of 1352 km arterials. In view of the potential wide coverage even for short time intervals, ''vehicle probes using cellular phones have been considered a promising technology for generating reliable travel time information'' (Yim, 2003).

The concept of cellular phones as probes has been explored by various researchers in simulation frameworks (e.g. Fontaine and Smith, 2005; Ygnace et al., 2000). Simulation studies have a major advantage since information about the exact location of each vehicle every second can be extracted from the simulation as ''ground truth'', which is rarely available in field tests. On the other hand, simulations can never replicate the entire complexities of reality; therefore, ''In order to make a full assessment, a field operation test is required'' (Ygnace et al., 2000).

Ygance (2001 cf. Yim, 2003) compared cellular phone-based speed data with loop detector speed data over a period of one month on four freeways in the vicinity of Lyon, France. The results in this study for an intercity freeway were that average speed according to loop detectors is about 10% higher than that obtained from cellular data (107.9 km/h southbound and 111.25 km/h northbound for loops compared with 100.5 km/h southbound and 99.4 km/h northbound for the cellular data). Larger average differences of 24–32% were found in the same study on an urban freeway. Observed cellular phone data exhibited substantial variations. It appears that average speeds above 100 km/h prevailed along both the intercity freeway and the urban freeway examined in this study at all times of the day. Such lack of congestion is a major limitation for a study of this type.

Smith et al. (2003) examined speeds measured by a point video sensor compared with cellular phone-based data for 39 intervals of 10 min each at different freeway locations, and for 35 intervals of 10 min each at different arterial locations. At freeway locations average speeds ranged from 14.2 mph to 68.7 mph; 22 intervals had speeds above 65 mph and nine intervals had speeds below 25 mph. At arterial locations, average speeds ranged from 12.8 mph to 46.7 mph; nine intervals had speeds above 35 mph and seven intervals had speeds below 25 mph. Average absolute differences between the two measurement methods were 6.8 mph for arterial locations, and 7.2–9.2 mph for freeway locations. The authors conclude that the "WLT-based system produced link speed estimates of moderate quality." Indeed it seems that while the reported system may not be able to meet the accuracy of 5 mph, noted by the authors as desirable, the system is probably capable of determining whether congestion prevails in a specific 10 min interval, information that many travelers are likely to consider as fairly useful.

The purpose of this paper is to present results from a case study that uses a new cellular phone-based system. The study includes comparison to loop detector data over a period of three months as well as comparison to floating car data. The remainder of this paper is organized as follows: The cellular phone-based system is described in Section 2. Comparisons between the measurement methods are presented in Section 3. Discussion and conclusions from the analysis are presented in Section 4.

2. The cellular phone-based system

As discussed in Section 1, a cellular phone-based system for travel time estimates relies on cellular phones carried in moving vehicles as data providing sensors. The system studied here was developed by Estimotion Ltd. (which is presently owned by ITIS Inc). The system focuses on handover events at which control of a presently used phone is handed over from one cell to another. Typically handovers occur about once a minute, and phone calls last 3–10 min. The system observes all handovers for every phone that is during a conversation, and their time stamps. For every handover the system computes the area in which the phone was located within probability of 85%, which is considered as the handover "footprint". An example of a sequence of such

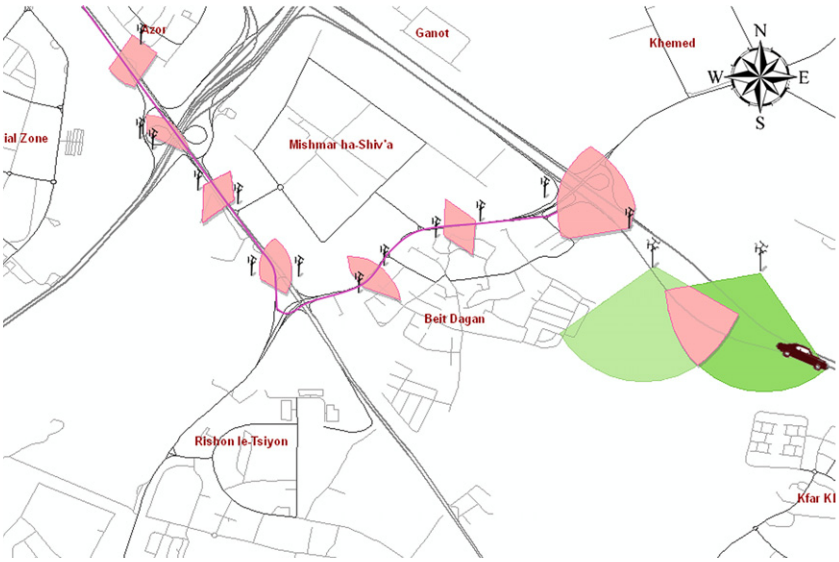

Fig. 1. Example of handover footprints generated by a moving vehicle.

footprints, generated by a moving vehicle, is illustrated in Fig. 1. The typical dimension of the handover footprint in the area considered in this case study is in the range of 300–1000 m.

Due to the relatively large size of footprints, matching individual footprints to locations on the road network is a difficult challenge. For example, a simple geometric map matching projects a given inaccurate position to the nearest location on the roadway network. Since this simplistic approach does not take into account past travel history or roadway network connectivity, estimated positions can often switch between parallel facilities (Fontaine and Smith, 2005). The cellular system studied here uses a different approach, in which a sequence of locations is matched to a route segment along the road network that appears to be the most likely. This is somewhat similar to the multiple hypothesis technique (MHT) (Pyo et al., 2001; cf. Fontaine and Smith, 2005).

Estimated routes are divided into road network sections, and the estimated travel time for every used phone over each road section is computed. All observations from different phones for a single section are analyzed together to produce an estimate of the travel time along that section. The analysis relies on proprietary algorithms that take into account the possibility that not all observations are actually related to vehicles traveling together with the regular traffic along the designated road section. For every 5 min interval this method is used to produce basic travel time estimates for all road network sections with available observations during the interval. These basic road section travel time estimates are the data analyzed in the present study.

The system also aggregates observations into a historical database. The historical database is used to fine-tune real time observations and fill gaps, where data is lacking in a certain time interval, in order to improve the information offered to travelers. These improved data are not considered in the present study.

3. Analysis

The analysis is based on data from January to March of 2005, regarding speeds along the Ayalon freeway, which is the busiest roadway in Israel, passing through the central business district of the Tel-Aviv metropolitan area. The freeway has four to five lanes in each direction and serves 600 000 vehicles every day (Ayalon Highways homepage, 2007). Typical daytime flows are in the range of 5000–10 000 vph. The main section of the Ayalon freeway, which is 14 km long with 10 interchanges, is equipped with a set of dual magnetic loop detectors for all lanes approximately every 500 m (60 stations). The loop detectors provided 1 284 587 (80%) valid (i.e. non-missing) mean speed measurements.

The cellular phone-based system received observations for about 1–3% of the total traffic during daytime (10:00–20:00), and generated 440 331 (63%) valid (i.e. non-missing) travel time estimates for 27 sections. Travel times were converted to average section speed simply as the ratio of road section length to estimated travel time. A schematic description of the roadway is given in Fig. 2. Vertical lines indicate separations between cellular system roadway sections. Loop detector stations are marked by x's.

There are many ways to examine the differences between such large datasets. For example, Smith (2006) recommends to public agencies to require that "Link travel time measures provided by the private sector shall have a maximum of 20% average absolute percentage error when compared to ground truth data," but subsequently indicates that a comparison of link travel time measurements with point speed measurements is not

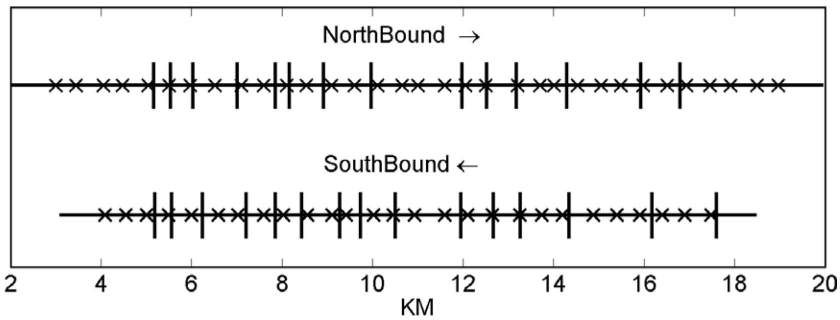

Fig. 2. Schematic diagram of the Ayalon freeway, its division to road sections, and loop detector locations.

necessarily "fair". Indeed, loop data can be considered as "ground truth" for link travel time measurements only when travel conditions are uniform. Obviously, in reality this is rarely the case. For example, when comparing speed measurements from neighboring loop detector stations, 500 m apart, the average relative absolute difference is 7% and the relative absolute difference is larger than 20% in 6% of the cases. Cellular system section lengths are 300–2000 m. When loop detector stations 2000 m apart are considered, the average relative absolute difference is 12% and the relative absolute difference is larger than 20% in 13% of the cases.

When loop detector point speed data are compared with cellular system estimates for the road section containing the point, the average relative absolute difference is 17% and the relative absolute difference is larger than 20% in 24% of the 631 005 comparisons. In view of the above mentioned loop-to-loop differences, the loop-to-cellular aggregate measures of deviation seem quite reasonable. While this type of aggregate analysis may provide a useful starting point for the evaluation, it is probably not sufficient to make a final judgment about the match between the two systems or about the quality of the cellular system.

When comparing huge datasets that represent complex phenomena such as traffic congestion, more detailed examination with consideration of the inherent time–space dimensions is likely to reveal additional important insights. For that purpose, graphical representations appear to be the most useful tool. In the following, speeds by time and location are presented in Section 3.1, and travel times along the entire roadway are presented in Section 3.2.

3.1. Comparison of speeds by location and time

Figs. 3–6 show speed by time and location. Each figure shows data for an entire single different day. Figs. 3 and 4 are for the southbound direction, and Figs. 5 and 6 are for the northbound direction. The top part of each figure shows loop data, while the bottom part shows the equivalent cellular data. The horizontal axis in these figures shows the time of the day, from 0:00 to 24:00. The vertical axis shows the location along the road in terms of the distance (in km) from the north end of the road. White areas in the figures indicate missing data. Other colors indicate the speed associated with the specific time–space combination, according to the scale on the right. In the case of the loop detectors, the reported speed is an algebraic average ("time–mean–speed") of the speeds of all vehicles on all lanes at the detector's location, for five minute intervals. In the graphical presentation these reported speeds are associated with a section of 500 m centered at the detector's location.

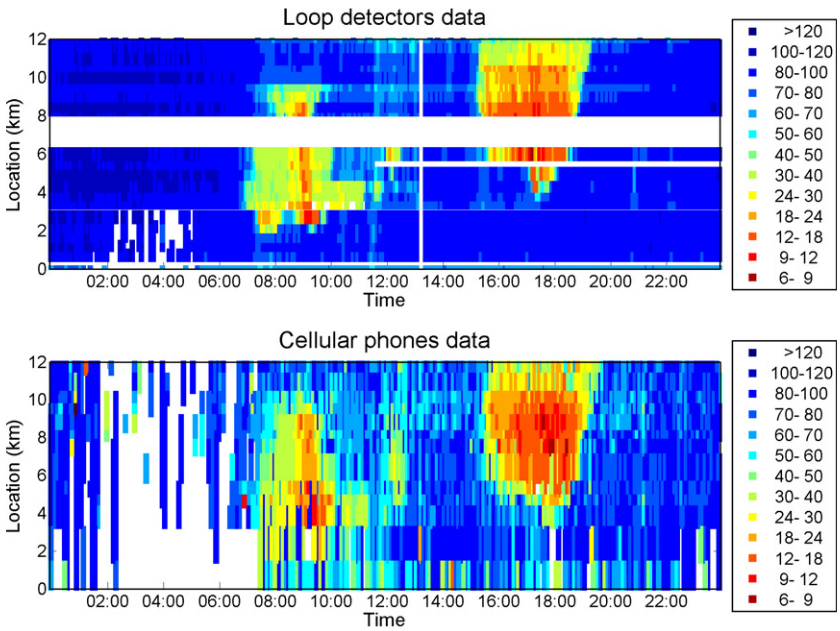

Fig. 3. Speeds (km/h) on Ayalon freeway southbound, Thursday, January 5, 2005.

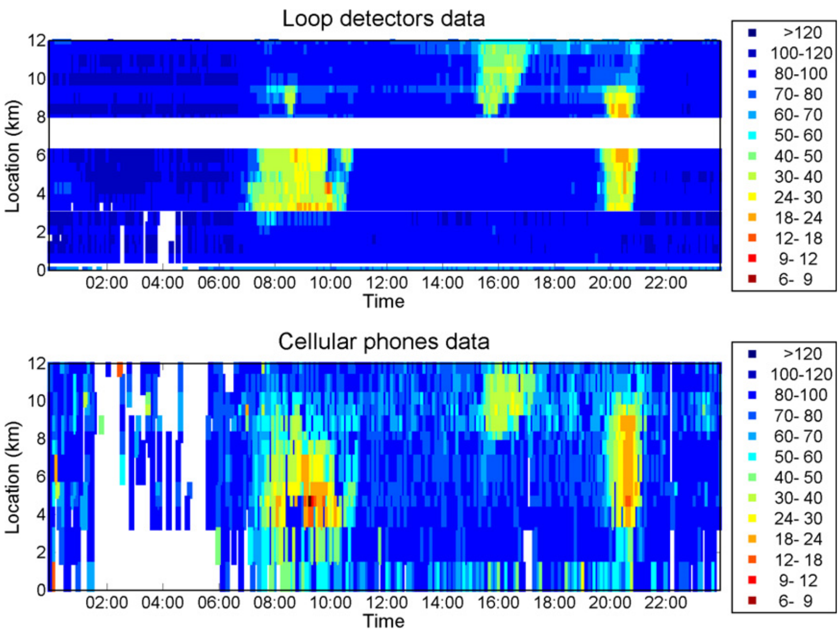

Fig. 4. Speeds (km/h) on Ayalon freeway southbound, Thursday, February 24, 2005.

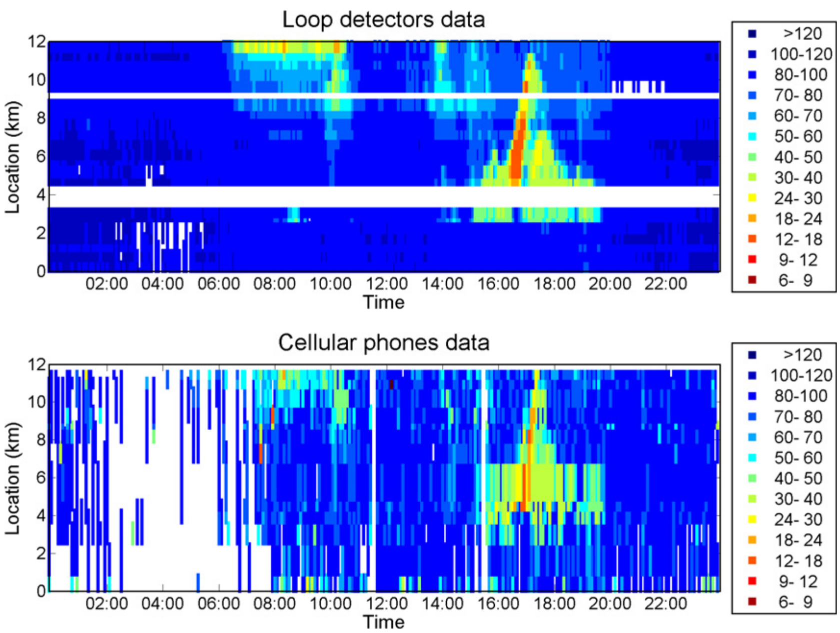

Fig. 5. Speeds (km/h) on Ayalon freeway northbound, Wednesday, February 2, 2005.

Fig. 3 shows the speed pattern for the southbound direction during Thursday, January 5, 2005. This pattern is dominated by very severe congestion, starting around 15:00 at a fairly complex interchange (Kibutz Galuyot) in the south end of the roadway (12 km), which is known to be a major bottleneck. At 18:00 the congestion reaches its peak length of nearly 9 km. The congestion eventually dissipates around 20:00. A secondary pattern of congestion occurs in the morning peak period, between 8:00 and 10:00, in the central section of the freeway, between locations 2–10 km. Both the morning and the afternoon congestion patterns are depicted in

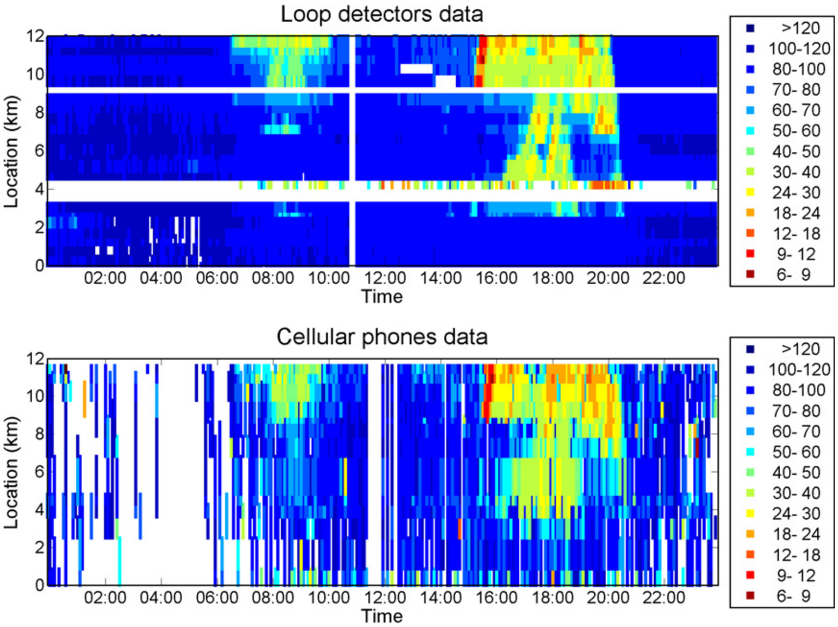

Fig. 6. Speeds (km/h) on Ayalon freeway northbound, Wednesday, March 30, 2005.

a similar fashion by the loop detector system and the cellular phone system. Fig. 4 shows the speed pattern on the southbound direction for a different Thursday, February 24, 2005. There are clearly major differences between this pattern and the one for January 5. In particular, the afternoon congestion was much milder, but there have been delays in the evening, around 20:00–21:00 at locations 3–9 km. The resemblance between the loop detector data and the cellular phone data in this figure is quite evident.

Figs. 5 and 6 show respectively the speed patterns in the northbound direction for Wednesday February 2 and Wednesday March 30, 2005. Again there are substantial differences between the two days, as well as essential agreement between the loop detector data and the cellular phone data with respect to the main elements of the speed patterns. I have examined 180 speed maps (for two directions over 90 days), and observed substantial variations from day to day, as partly demonstrated in Figs. 3–6. The overall impression from these figures is that there is a good match between the time–space speed patterns as depicted by the cellular phone system and those depicted by the loop detector system.

During the study period, the loop detectors at several locations did not work at all, as shown in the figures by the horizontal white bands. Occasionally other detectors did not work as well, but overall the loop detector system was functioning properly during most of the study period. The cellular phone system provided information in real time during most of the study period as well. The scope of the current study was the daytime period (7:00–24:00), and therefore I did not analyze the night-time behavior at this stage of the research.

The last observation from these figures is that the cellular phone data appears to be somewhat more "noisy" than the loop detector data. An aggregate measure for the noise can be the average absolute relative difference between travel time estimates for consecutive 5 min intervals (at the same road section), which is 14% for the cellular data and only 4% for the loop detector data. The differences when comparing 5 min intervals that are 15 min apart are 15% and 5% for the cellular and loop data, respectively. The similarities in the values suggest that these differences are indeed mainly due to noise and not due to changes in the traffic conditions. A possible explanation for the larger noise in the cellular system is the use of smaller sample sizes. The noise appears to be more noticeable particularly in the first section of the southbound direction (0–1.5 km). This is possibly due to the fact that at the time of the study all vehicles in this section came from an on-ramp, as the through section was not built yet. Additional evaluations of these noise effects and their practical implications remain a subject for future research.

3.2. Comparison of travel times

The second step of the analysis focused on travel times along the entire roadway, as demonstrated by Figs. 7 and 8 for January 16th southbound and for January 18th northbound, respectively. Total travel time for every time interval according to the cellular phone data was computed simply as a sum of the travel times of all the segments along the road at the same time interval. In the event of missing data in one of the segments, total travel time was not computed. Considering loop detector data, for the purpose of the total travel time computation, the distance between every two consecutive working detectors was divided into two, the speed of one detector was associated with the first half and the speed of the other detector was associated with the second half. Note that this computation assumes uniform conditions between loop detectors; hence the resulting estimated travel time cannot be considered as ground truth. When part of the detectors did not work they were considered as if they did not exist, and as if the detector before and the detector after were consecutive (In the southbound direction the resulting distance is 2 km between one pair of consecutive working detectors). When more than half of the detectors did not work, total travel time was not computed.

Comparisons of computed travel times from both systems and floating car measurements are shown in Figs. 7 and 8. Fig. 7 shows the comparison for January 16, 2005 in the southbound direction, and Fig. 8 shows the comparison for January 18, 2005 in the northbound direction. Both figures show a good match between all three methods to measure travel times. According to these figures there seem to be a constant bias of about 1 min between the travel times computed from the cellular phone data and those computed from loop detector data, especially during uncongested times.

An aggregate comparison for the entire three-months period for both directions of travel is shown in Fig. 9, where the horizontal axis represents the travel time computed from the loop detectors data and the vertical axis represents the travel time computed from the cellular phone data. It is important to point out the semi-log color scale used to represent the number of observations (5 min time intervals) for each combination of computed travel times. In particular, out of 20 368 valid comparisons, computed times for both systems are in the range of 8–10 min in 13 348 (65%) of the cases; four of these nine combinations occur more than one thousand times each. At the other extreme, computed travel time combinations of substantial disagreement are mostly of the lightest color, thus representing a single observation (one 5 min interval) each. Overall the figure shows that for the most part there is good agreement between the travel time estimates from both systems.

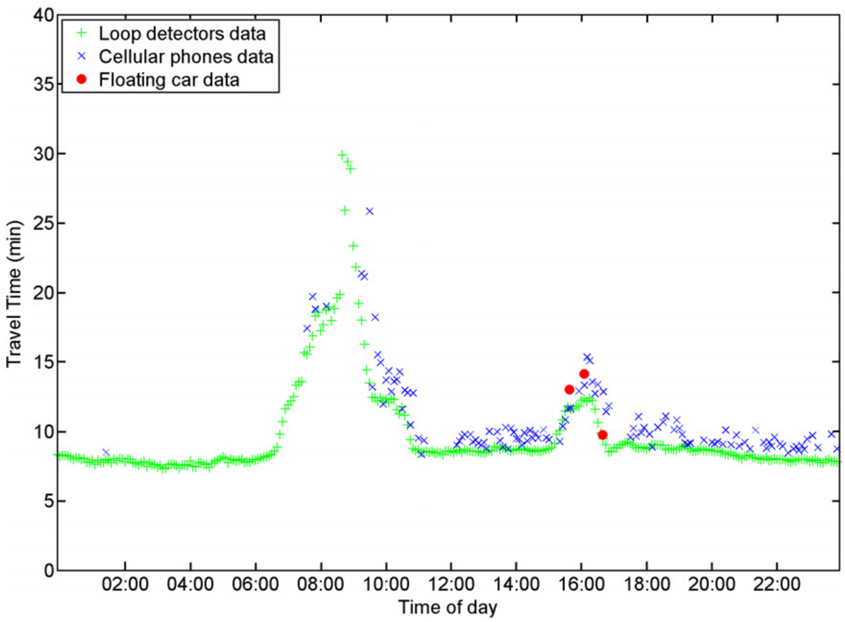

Fig. 7. Travel times on the Ayalon freeway southbound, Sunday, January 16, 2005.

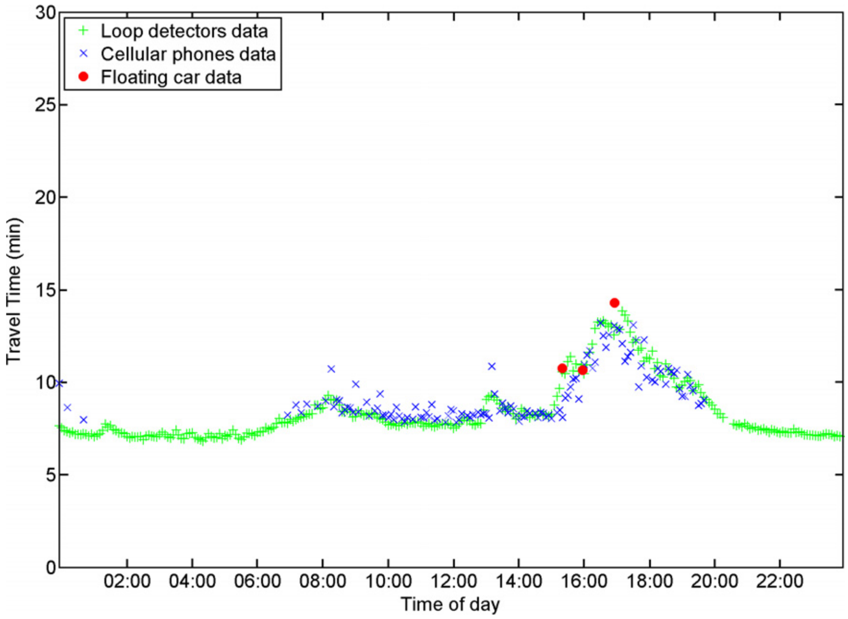

Fig. 8. Travel times on the Ayalon freeway northbound, Tuesday, January 18, 2005.

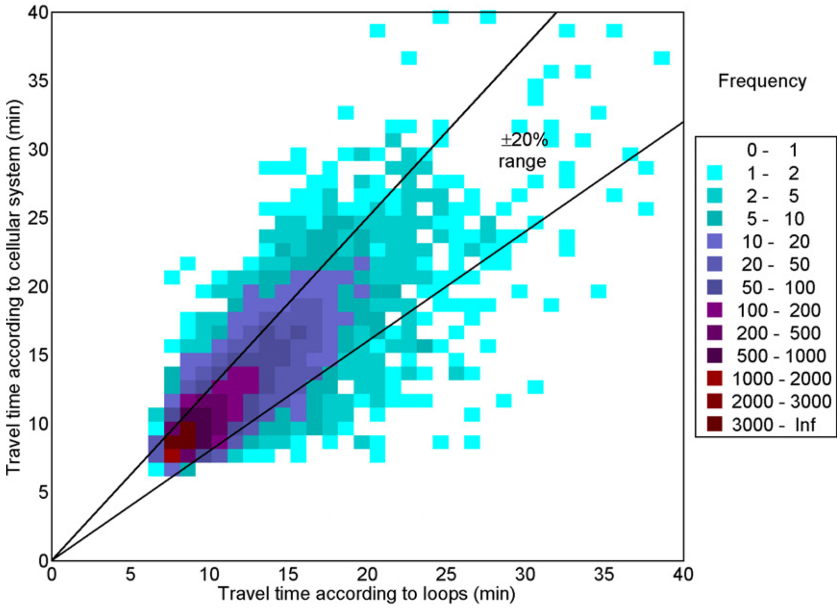

Fig. 9. Summary comparison of computed travel times from loop detector data and from cellular phone data.

Considering 20 368 time intervals during workdays in the three-months period from January to March of 2005 for which travel times were computed from both loop detector data and cellular phone data, the average absolute relative difference is 10.7%; in 88% of the cases the absolute relative difference is less than 20%; the total average difference is 0.57 min; and the average absolute difference is 1.09 min.

A breakdown of these differences is shown in Table 1. For this breakdown intervals when the loop detector travel time is 15 min or more are considered as congested. The last column in the table shows the average

Table 1
Comparison statistics for travel time computations between loop detector data and cellular phone data

Direction	Congestion[a]	# Obs	Ave TT	Δ_1[b]	Δ_2[c]	Δ_3[d]
Southbound	No	9268	9.47	1.03	1.22	0.85
Southbound	Yes	969	18.35	0.27	3.11	3.10
Northbound	No	9934	8.64	0.22	0.71	0.66
Northbound	Yes	197	18.28	−2.03	3.98	3.66

[a] Congestion is defined as periods when the travel time according to the loop detectors is longer then 15 min.
[b] Average loop to cellular difference (min).
[c] Average absolute difference (min).
[d] Average absolute difference, compensated for average difference (min).

absolute difference with a compensation for the difference in the means. The three difference values are defined as follows:

$$\Delta_1 = \frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - y_i); \quad \Delta_2 = \frac{1}{n} \cdot \sum_{i=1}^{n} |x_i - y_i|; \quad \Delta_3 = \frac{1}{n} \cdot \sum_{i=1}^{n} |x_i - y_i - \Delta_1|,$$

where x_i is the loop detector observation and y_i is the equivalent cellular phone observation. The good agreement between the two systems during non-congested intervals is quite reassuring. During intervals that are considered as congested the average travel time is 18 min, while the differences between the systems during these intervals are 3–4 min, which seems to be quite acceptable.

To further validate computed travel times, 25 floating car measurements taken within a single week were used, as shown in Fig. 10 (six of them are shown specifically in Figs. 7 and 8). Again the overall correlation is good, with four outliers in which the floating car measurements are substantially longer, while the computed values from the two systems are quite similar. Fig. 11 shows the residual (computed-measured) travel time, excluding the four outliers discussed above. The average difference between the computed travel times from loop detector data and the floating car measurements is 0.9 min, and the average absolute difference is 0.93 min. The equivalent values for computed travel times based on the cellular phone data are average difference of 0.49 min and average absolute difference of 1.07 min.

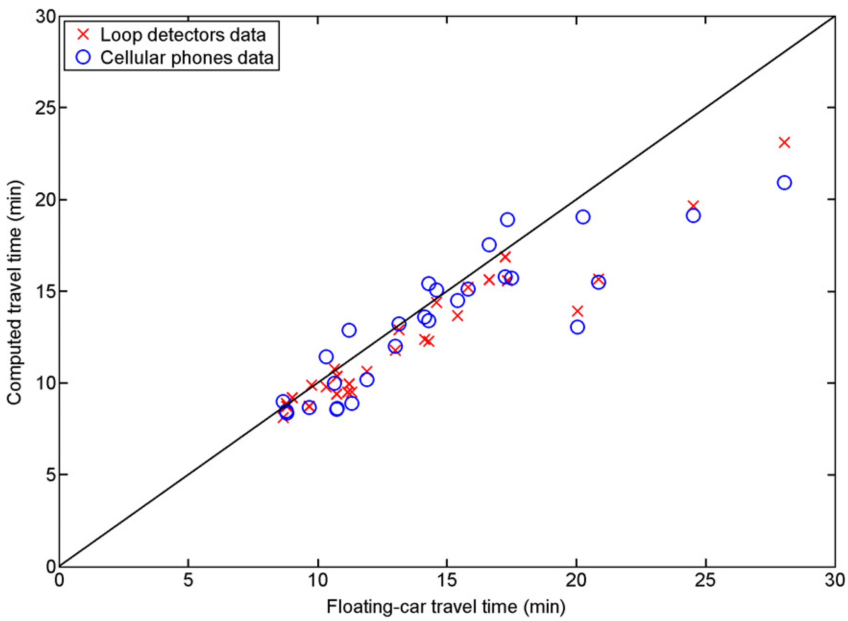

Fig. 10. Computed travel times vs. floating car travel time (25 observations).

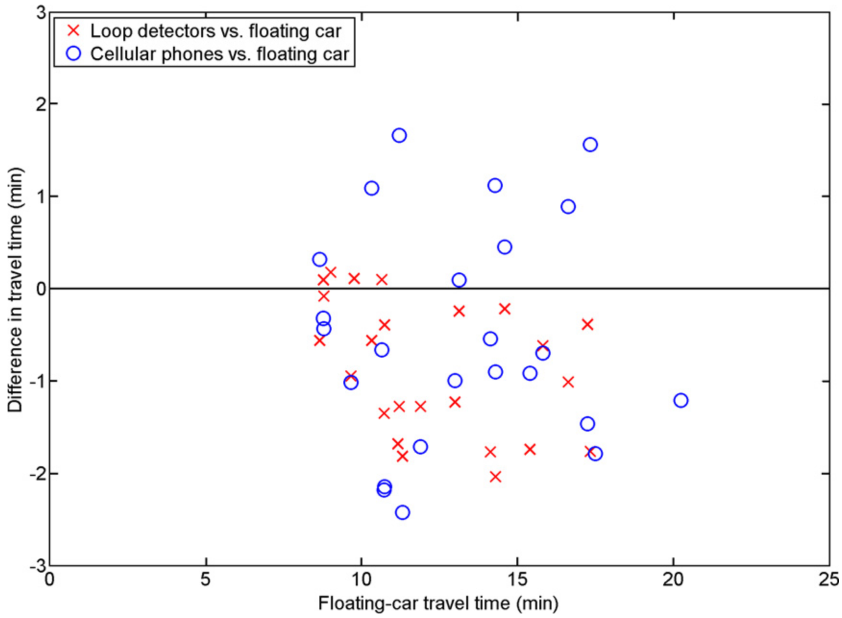

Fig. 11. Residuals of computed travel times compared to travel times measured by floating cars (21 observations, four outliers excluded).

The available data is not sufficient for identifying the most accurate measurement method, as we do not have data that can be considered as ''ground truth''. Floating cars provide a small sample, influenced by the ability of their drivers to maintain a similar speed to the surrounding traffic, and the limitations of measurement equipment accuracy. Loop detector data may suffer, for example, from: missing detectors; the use of time–mean–speeds; the aggregation of vehicles on all lanes including vehicles that arrived from an on-ramp or directed to an off-ramp; etc. The cellular system is also subject to potential biases, for example due to differences between the population of cell-phone users and the general population. Evaluating the magnitude of these biases remains a subject for future studies.

4. Discussion and conclusions

In this study I compared speed and travel time measurements from a system that is based on cellular phone data with the equivalent data from dual magnetic loop detectors for a 14 km freeway over a three-month period. Overall, the correspondence between the two systems is good. Floating car travel time measurements provided additional assurance for data accuracy. According to these analyses, the cellular phone data appears to be suitable for usage in practical applications, especially for ATIS as well as modeling, planning and management of transportation infrastructure investments.

Users of data from the cellular phone system at its current status should take into consideration its potential limitations. The main one is the "noise" that accompanies the measurements. Additional studies are needed to quantify these effects more precisely and to evaluate their implications for different applications.

Considering the positive results with the cellular phone-based system for measuring speeds and travel times, as reported here, and the potential for further improvements and enhancements, it seems reasonable to anticipate increasing usage of this approach in the coming future.

Acknowledgements

Financial support from ITIS inc. and Estimotion Ltd. is greatly appreciated. The author wishes to thank Uri Lavee and Israel Feldman from Estimotion Ltd. for their collaboration and for the cellular phone system data. The author also wishes to thank Ayalon Highways Company and their Traffic Control Department team, Vedran Kulic and Lev Krasilashikov, for providing loop detectors data and for their collaboration. Valuable comments from four anonymous referees contributed to improve the paper. The opinions expressed in this paper reflect the views of the author only.

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