Assessment of Travel Time Estimates based on Different Vehicle Speed Data: Spot Speed vs. Sampled Journey Speed in South Korean expressways

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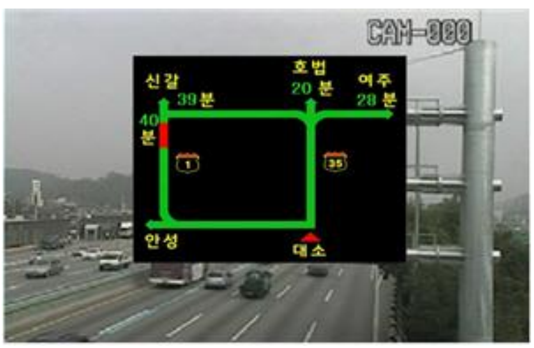
Abstract: This paper empirically compares travel speeds measured by two different sensing methods – i) instantaneous speeds of all vehicles passing fixed locations over time (loop detectors) versus ii) actual travel speeds of sampled vehicles over the distance by re-identifying them at two distant locations (electronic toll transponders). This comparative study shows that traffic data from loop detectors overestimated vehicle speeds when traffic was congested. This bias was systematic such that the overestimated vehicle speeds could be corrected by statistically formulating the relation between speeds measured by two methods. The findings show that the difference between two speed measurements (speed from loop detectors – speed from ETCs) and actual speed are correlated positively and form a well-defined linear relation.

Keywords: Travel Time, Time-mean, Space-mean, Loop Detection, Electronic Toll Collection, Traffic Sensing

1. INTRODUCTION

Real-time traffic information has been used worldwide to monitor operational status of transportation networks and to help commuters travel more conveniently and efficiently. With the advancement and penetration of Information and Communication Technologies (ICT) in our daily trips, we are entering the new era of gathering and providing the traffic information.

In South Korea, real-time traffic information has been collected by many transportation authorities and disseminated to public. Korean expressway cooperation (EX) is one of the leading authorities in this perspective as they deploy increasing number of variable message signs for displaying traffic information as well as other services such as ROADPLUS (ROADPLUS, http://www.roadplus.co.kr) as shown in Figure 1.



(a)


(b)


(c)

Figure 1. Traffic information services provided in Korean Expressways: (a) Variable Message Sign in Korean Expressway; (b) Mobile App; and (c) Website

Not only disseminating traffic information, There has been extensive efforts devoted to collect more accurate information. For monitoring purpose, closed circuit TVs (CCTVs) and loop detector stations have positioned in every 2~3 km and 1 km, respectively in Korean expressways. Recently, a large number of roadside equipment (RSE) has been installed to measure travel times from vehicles with electronic toll collection (ETC) transponders. Although they can measure actual travel times, reliability of travel time estimates is dependent on the number of vehicles with transponders as RSE communicates only with transponders *via* dedicated short range communication (DSRC). However, as more vehicles use ETCs, the more accurate and reliable travel information could be archived and analyzed.

These two detection methods based on loop detectors and ETCs produce time-mean and space-mean speeds, respectively. The former is not actual travel speed but instantaneous speed measured at fixed locations (Cassidy and Coifman, 1997; Soriguera and Robuste, 2011; Wang and Nihan, 2000). Even with high penetration of ETCs, however, travel time estimation still relies much on loop detectors. This is because loop detectors are prevalent over the expressway networks and are capable of measuring travel times of all the vehicles passing over detectors while ETCs are equipped in sampled vehicles only. The objectives of this study are: i) to examine whether travel speeds measured by loop detectors and ETCs are different; and ii) if exists, to evaluate the difference between two measurements. To these ends, the remainder of this paper is organized as follows: Background information on sensing methods and potential errors in loop detectors is reviewed in Section 2. Descriptions on data and study site are furnished in Section 3. Collected data are analyzed in Section 4. Finally, the implications are drawn from the data analysis in Section 5.

2. BACKGROUND

Traffic sensors measure three traffic characteristic parameters defined in time and space domain – flow (vehicles per unit time), density (vehicles per unit distance) or occupancy (%), and speed (distance per unit time). Although all three parameters are important in traffic engineering, vehicle speeds are the most useful information from a driver's perspective because it is directly related to their travel times. Due to practical and technical limitations of the current sensing methods, however, it is almost impossible to track all vehicle speeds on a roadway. In Korean expressways, two different types of measurements are collected. The one is to measure vehicle speeds passing at a fixed location (i.e., time-mean speed) by using loop detectors and transform the measurements as if they are travel speed over the distance. However, speed measurements obtained from this method are not actual travel speeds because instantaneous speeds averaged among several vehicles does not account for the difference in travel time for the vehicles that are traveling at different speeds over the same distance. The other method is to re-identify vehicles at predetermined locations along their travel path, and to record their passing times. The passing times are then converted to vehicle speeds. With the recent penetration of ETC transponders in Korean Expressways, vehicle re-identification becomes more prevalent. In this section, aforementioned sensing methods are further described (Section 2.1) and the potential differences between two different types of sensing methods are reviewed (Section 2.2).

2.1 Sensing Methods

2.1.1 Spatially stationary detection (traditional approach)

Vehicle detection of this type detects vehicles passing or arriving at a certain point, for instance approaching a traffic light or in motorway traffic (Figure 2). Sensing technologies such as inductive loop detector, radar, video camera, etc. belong to this category and produce time-mean travel speed. In Korean expressway, loop detectors are installed in every 1 km and record vehicle count, occupancy and vehicle speed in 30-sec interval. The data are aggregated and provided upon request.

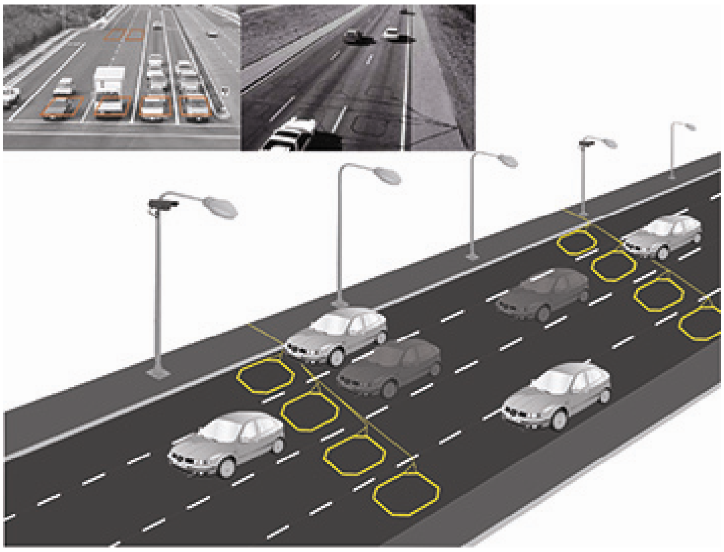


Figure 2. Spatially Stationary Detection

Pros
- Collect traffic information of all vehicles passing the detection location.

Cons
- Obtain information only where detectors are installed.
- High cost for installation and maintenance.

2.1.2 Vehicle re-identification

Devices in vehicles often have capability to communicate in short range, for instances, electronic toll collection transponder, plate number identification, blue tooth, etc. This type of devices is unable to communicate continuously, but can be used to be identified by roadside readers. By identifying vehicles with these devices in consecutive locations, one can estimate section travel time and, therefore, produce space-mean speed. The devices of this type can also estimate positions of vehicles in space and time, and their average travel speed. In Korean expressways, ETC transponders, so-called Hi-Pass, are used to this end.

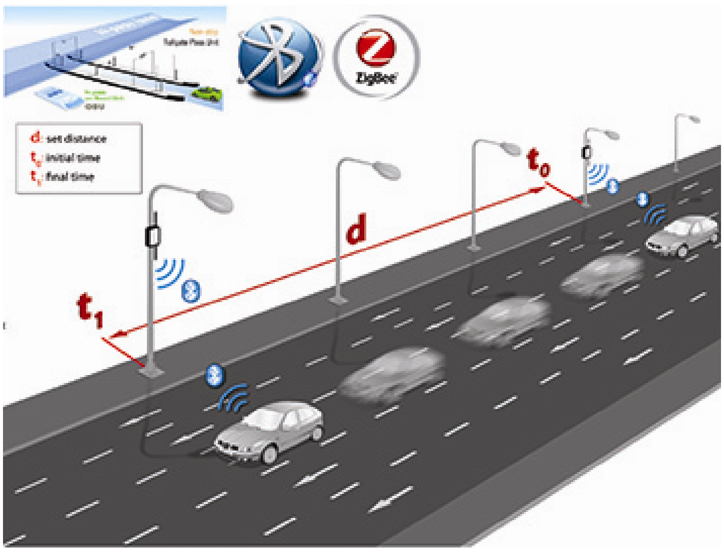


Figure 3. Vehicle re-identification detection

Pros
- Estimate actual travel time.
- The devices can be used for other purposes and thereby encouraging penetration in traffic.

Cons
- Dependent on the locations of roadside reader.
- Privacy issues.

2.2 Potential Errors

As described in section 2.1, sensing methods based on spatially stationary detection include potential error sources. This section reviews three potential errors that may occur in using data from spatially stationary detection, especially loop detectors, because loop detectors are used in the study site.

1) Detector errors
Since the spatially stationary data used in this study are from inductive loop detectors, inductive loop detector errors are reviewed (Coifman, 2001; Coifman and Dhoorjaty, 2004).
   a) **Hardware Malfunctioning**: this type of errors occur when detector circuit or controller are not functioning properly. This error would produce zero values.
   b) **Pulse breakups**: a single vehicle triggers multiple detections because on and off signals are registered more than once for a single vehicle due to induction pulse breakups.
   c) **Erroneous choice of threshold**: threshold value for pulse detection is set too high or low such that the detectors react more or less frequently than they need to be.
   d) **Erroneous choice of g-factor**: Since single loop detectors only measure vehicle count and occupancy, speed are estimated by using g-factor, the effective vehicle length. Error in selecting g-factor would directly result in errors in speed estimates.

2) Errors due to transitions in traffic states
Errors can occur when transitions from free-flow to congestion or *vice versa* are not detected by loop detectors. Figure 4 illustrates travel time difference with and without considering transitions in time-space diagram (i.e. $T_A – T_E$). The shaded area is congested region in time-space domain. The black-solid line indicates actual travel time that can be estimated by using vehicle re-identification method. The black-dotted line is the trajectory that may be produced based on the point measurements at the location indicated as horizontal dotted lines. Please note how the estimated travel times, T_A (actual travel time) and T_E (erroneous travel time), are different.

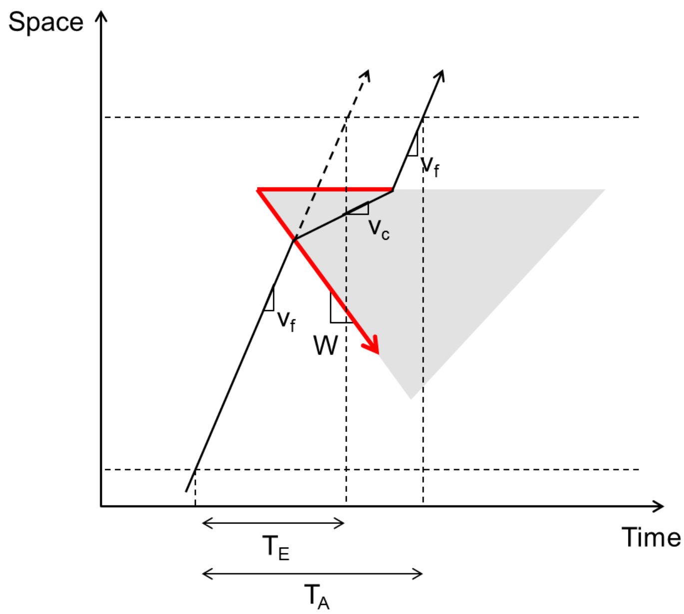


Figure 4. Time-space diagram of two different sensing measurements

3) Difference between time-mean and space-mean speeds
The speed measurements obtained from the loop detectors rely on instantaneous speeds at point locations. This type of speed measurements produces time-mean speed. It is well known that the time-mean speed is different from the space-mean speed, the journey speed (Wardrop, 1952). Wadrop (1952) and Rhkha and Zhang (2005) proved

that, if traffic is stationary, there is a quantitative relation between time-mean and space-mean speeds as follows:

$$V_T^2 = V_S^2 + \frac{\sigma_S^2}{V_S}$$

Where, V_T is time-mean speed, V_S is space-mean speed, and σ_S is standard deviation of space-mean speed.

This shows that time-mean speed is equal or greater than space-mean speed by the amount of σ_S^2 / V_S, which increases when traffic becomes congested. This is because V_S diminishes while variations in speed increase, σ_S^2, due to stop-and-go movements under congestion. Consequently, V_T becomes even greater than V_S when traffic is congested.

Although potential errors are identified as above, it is almost impossible to isolate each error. This study, therefore, evaluates errors of all three together and performs quantitative evaluation on the difference between two different measurements.

3. DATA AND SITE DESCRIPTIONS

The site used in this study is the segments of Seoul-bound Gyeongbu Expressway that extends from Anseong to Giheung-Dongtan Interchanges as illustrated in Figure 5. In majority of segments, there are four lanes including one bus lane in Median. In the analysis, traffic data from the bus lane are not used. Multiple bottlenecks reside along this 26.4-km stretch and recurrently become active during afternoon peak hours both in weekdays and weekends. Congestion patterns are diverse and vary with demand patterns for this site.

In the Korean expressways, travel times are collected from two different types of sensing methods described in Section 2.1 – spatially stationary sensing by using inductive loop detector and vehicle re-identification by communicating with electronic toll collection (ETC) transponders.

The 23 loop detector stations for measuring traffic data are installed in the study site and indicated as blue marker in Figure 5. The numbers annotated next to the markers are post-kilometer adopted by Korean Expressway system. The detectors record counts, occupancies and time-mean speeds (i.e. speed measurements at a fixed location over time) in each lane over 30-sec intervals. Korean Expressway Cooperation is responsible for collecting, handling and distributing the data. The traffic data were aggregated and provided in 5-min intervals.

ETC system in Korean Expressway, Hi-Pass, uses two different types of technologies for transponders, radio frequency (RF) and infrared ray (IR), *via* dedicated short range communication (DSRC). Along the expressway, eight readers (seven sections) are installed roadside and record passing time and transponder ID when vehicles with transponders pass the roadside readers. Hence, one can compute travel time between two consecutive roadside readers by subtracting times recorded from them (see Figure 6). The locations of roadside readers are labeled as green triangle is Figure 5.

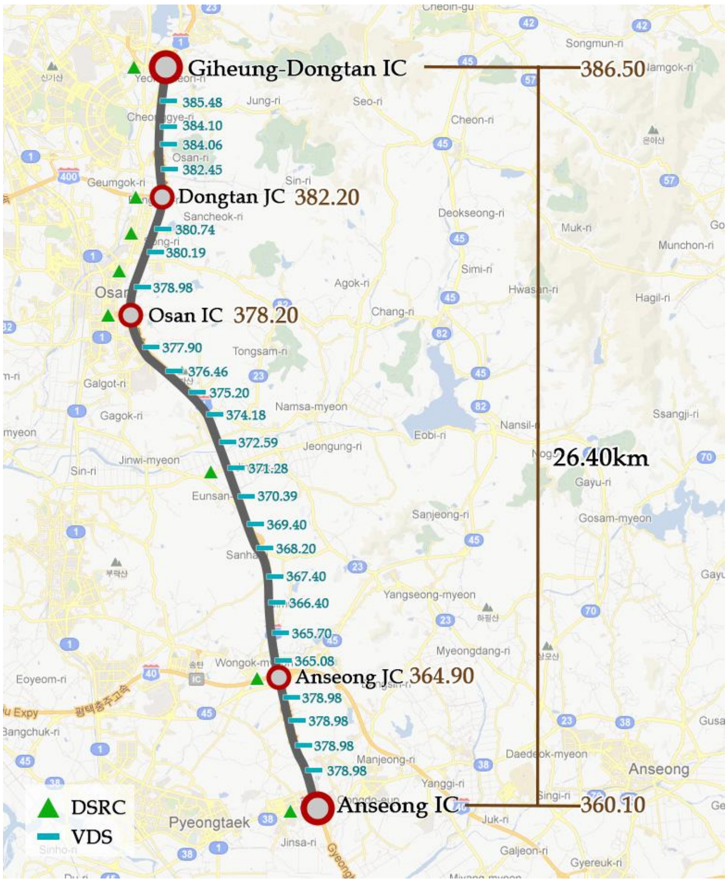


Figure 5. Study site

Figure 6. Hi-Pass Transponder

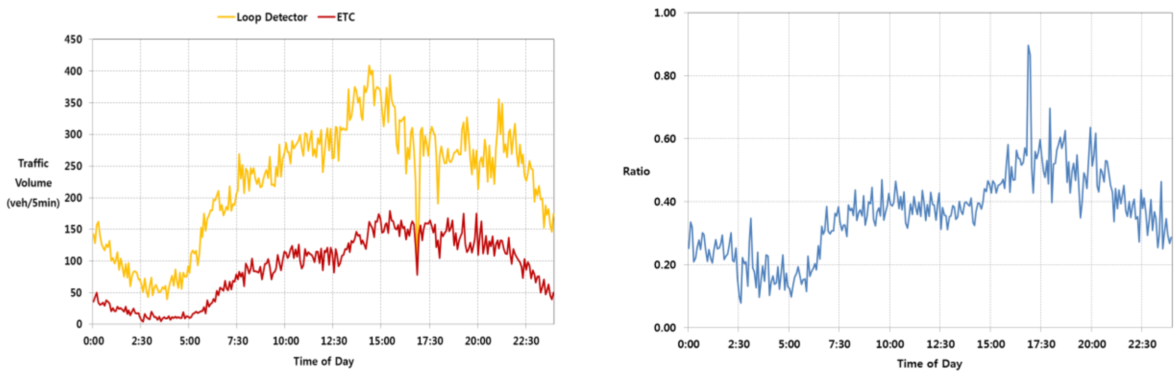
4. DATA ANALYSIS

This section documents findings from traffic data analysis. In the study site, the percent of vehicles with ETC transponders in traffic is high enough to gather accurate traffic information (Section 4.1). Time-series speed profiles constructed based on two data sources – loop detectors and ETCs – can reflect congestion patterns quite consistently. However, data from loop detectors are tend to overestimate travel speed, especially when traffic is under congested regime (Section 4.2). The overestimated tendency shows regularity (Section 4.3). In this study, one week of traffic data are obtained and analyzed. Among those data, three days of traffic data (April 14th, 2011 (Thursday); April 15th, 2011 (Friday); and April 17th, 2011 (Sunday)) are presented in this section.

4.1 Penetration rate of Hi-Pass in the study site

As the first step, penetration rates of ETC transponders are examined whether actual travel times from a subset of traffic (vehicles with ETC transponders) can represent the entire traffic traversing our study site. Previous study (Hoh et al, 2008) shows that 1~2% of penetration rate could generate accurate traffic information. To calculate penetration rate, we randomly select a section whose boundaries are two consecutive RSEs and a loop detector installed within the section. The number of vehicles detected by RSE and loop detector is counted and compared in Figure 7(a). Since RSE only counts the number of vehicles with ETC transponders while loop detectors detects all the vehicles passing, the penetration rate can be calculated simply by taking the ratio of vehicle counts registered by RSE to those measured by loop detectors. Figure 7(b) displays this ratio. Data used in Figure 7 are from April 15th, 2011, as an example. Similar patterns are reproduced in other days.

Traffic volume in this section of expressway is quite high during afternoon peak hours. The number of vehicles detected by RSE exhibits similar patterns – increasing during afternoon peak hours. The time-series ratio profile in Figure 7(b) indicates that the penetration rate remains above 40% since the onset of congestion around 3 PM. Traffic volume and ratio data together signify that the route is heavily used during afternoon peak hours and the penetration of ETCs is high enough to use ETC data as actual travel times.



(a) **(b)**

Figure 7 (a) traffic volumes measured by RSE and loop detector; and (b) percent of ETC penetration in traffic (April 14, 2011)

4.2 Congestion vs. Traffic Speed

This section evaluates how congestion patterns are reflected in traffic speeds measured by loop detectors and ETCs. First, we used detector occupancy data (i.e. a dimensionless measure of density). Top figures in Figure 8-10 (a) present spatiotemporal plots of occupancy from all the loop detectors along the stretch of our study site. Note in interpreting the figures: (i) red color indicates high occupancies, meaning the site is congested; and (ii) the boundaries between red and green indicate spatiotemporal transition between free-flow and congestion. Top figures in Figure 8-10 (a) show that the route is recurrently congested during afternoon peak hours and multiple bottlenecks activate depending on demand patterns.

Since loop detectors measure travel speed at fixed locations, it is needed to take distance into account in calculating average speed:

$$V(t) = \sum_{i=1}^{n} \frac{V_i(t) \cdot C_i}{d_i}$$

Where, $V_i(t)$ is the speed measurement at loop detector i at time t; $d_i(t)$ is the distance between loop detectors i and $i+1$; C_i is the coverage by loop detector i at time t ($=(d_i + d_{i+1})/2$); and n is the total number of detectors.

However, the loop detectors measure the speed intrinsically at an instantaneous time. Travel speed measured by loop detectors is unable to reflect spatial variations of traffic conditions. Travel speed from loop detectors are displayed in blue solid line in Figure 8-10 (b). On the other hand, ETC transponders directly measure travel time between two measurement locations and, thus, travel speed can be derived by dividing the distance between two locations by the measured travel time. Four descriptive statistics – max, min, median and mean – are displayed on the graph to show the speed distribution.

The time-series speed profiles in the bottom figures of Figures 8-10 show that the measured speeds well represent the congested patterns, i.e. speed varies simultaneously with the changes in congested distances. Speeds measured by loop detectors are within the range of speed measured by ETCs. However, some systematic differences were observed in all three bottom figures: speeds measured by loop detectors are higher when speeds become slow or *vice versa*. This pattern indicates that the speed measured by loop detectors are less sensitive to the congestion than it needs to be, and, thus, is biased.

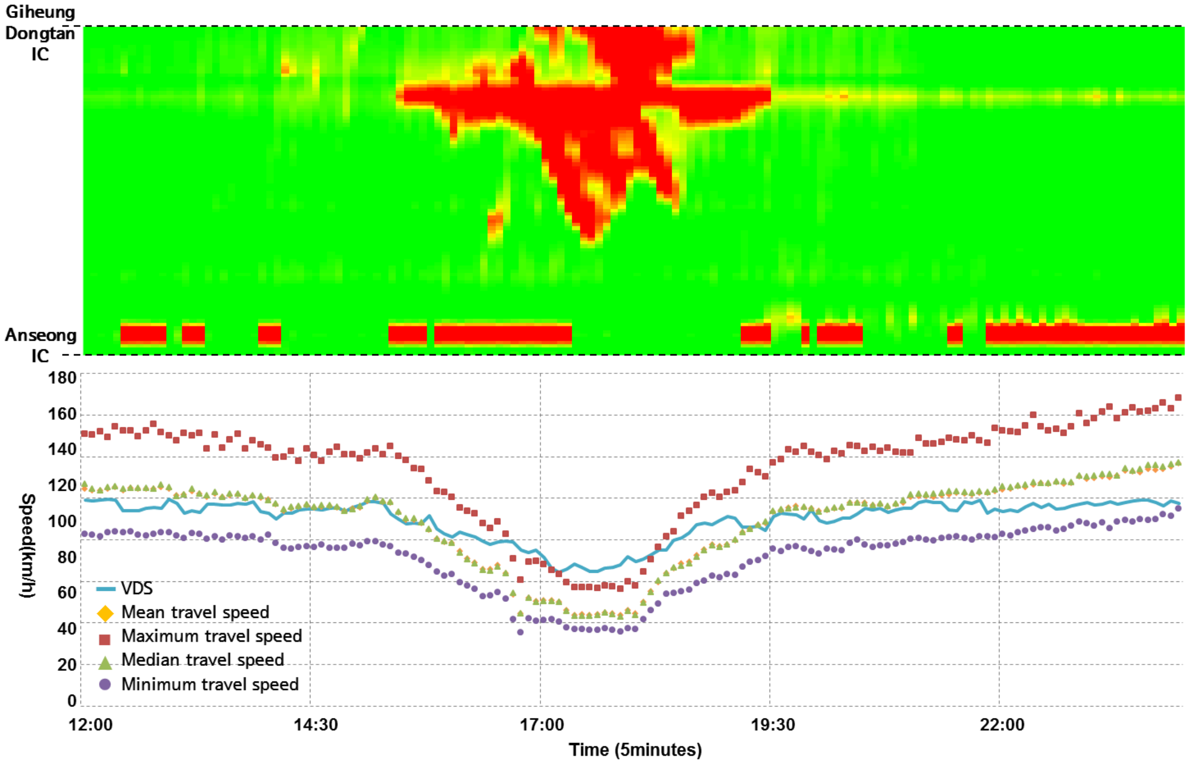


Figure 8 spatiotemporal occupancy contour plot (top); time-series speed profiles (bottom)

(April 14th, 2011)

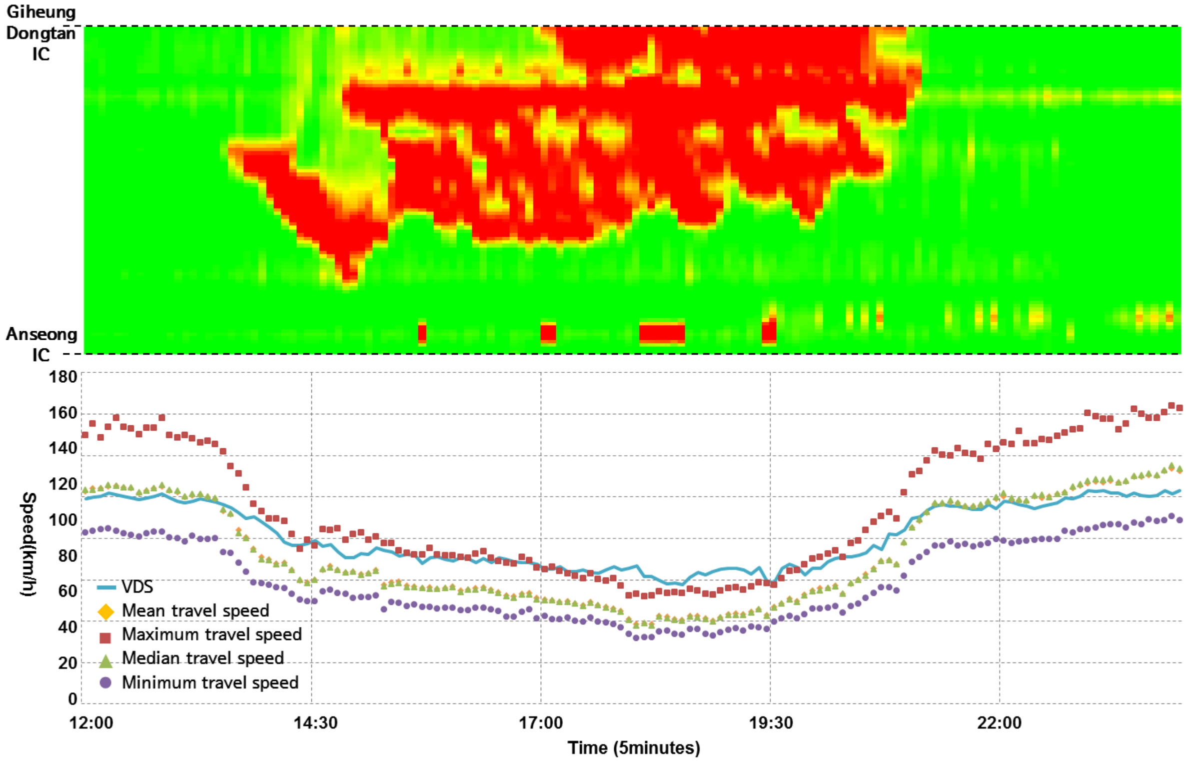


Figure 9 spatiotemporal occupancy contour plot (top); time-series speed profiles (bottom)
(April 15th, 2011)

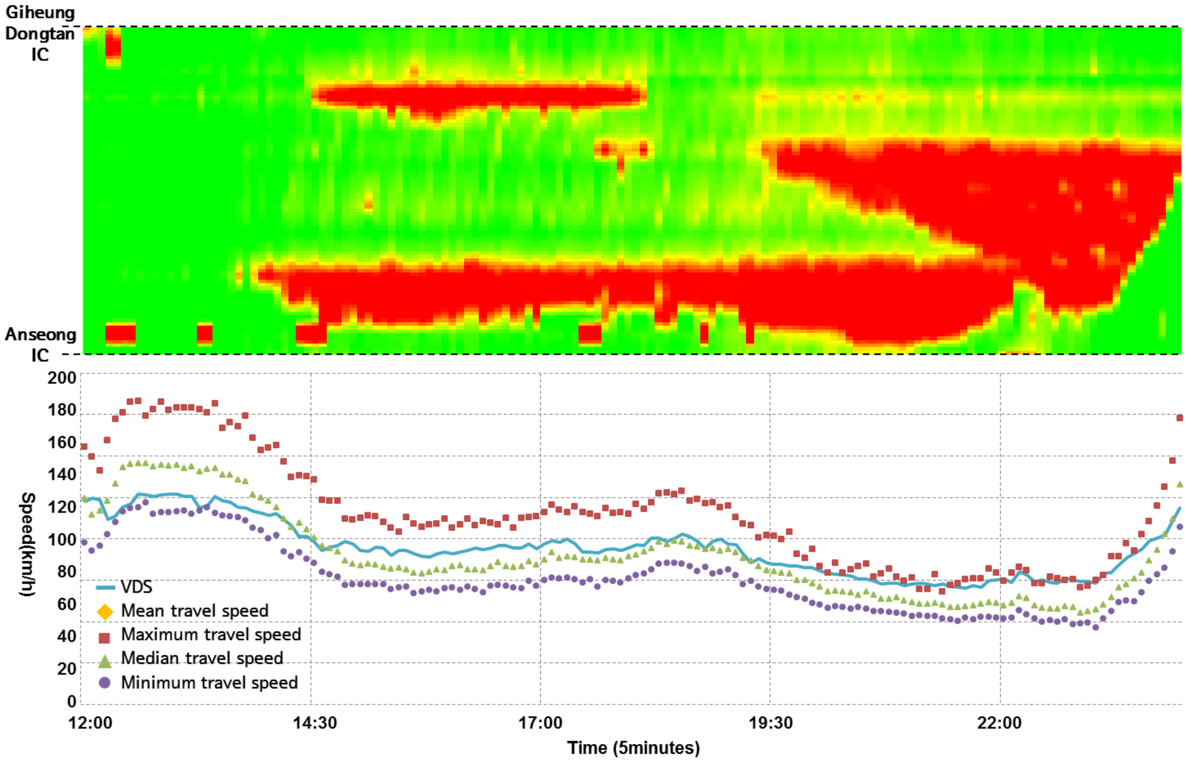


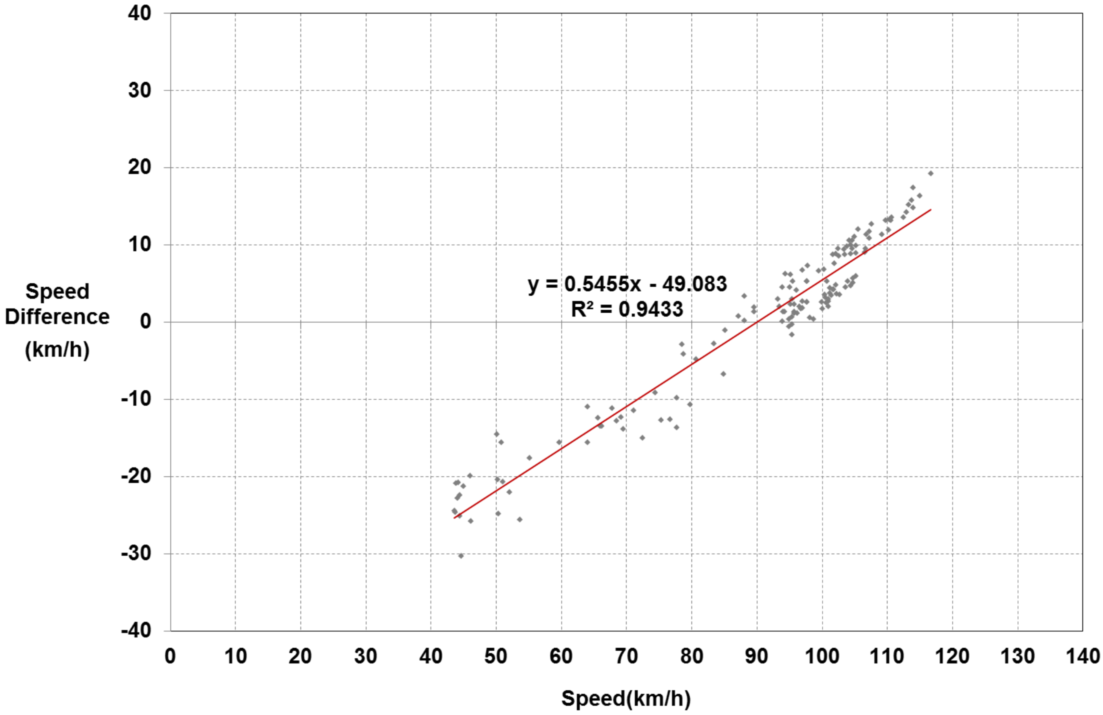
Figure 10 spatiotemporal occupancy contour plot (top); time-series speed profiles (bottom)
(April 17th, 2011)

4.3 Traffic Speed vs. Speed Difference

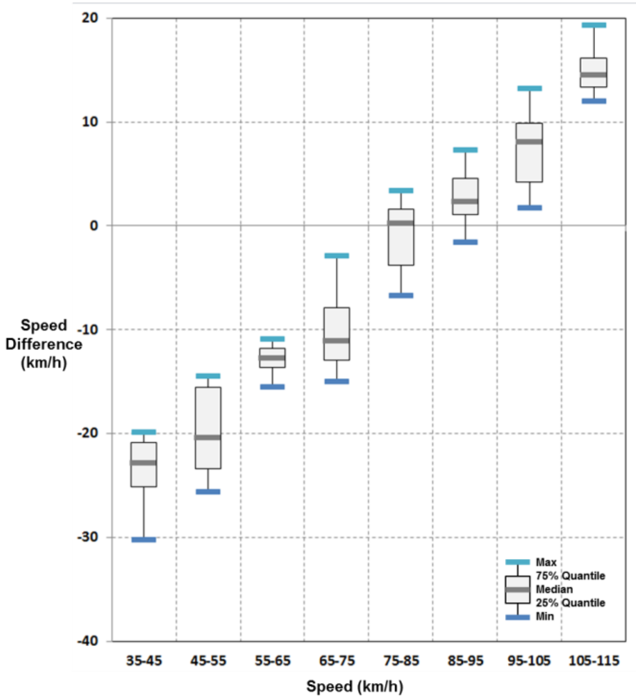
Visual inspection on Figures 8-10 show that speed data from loop detectors are systematically biased. In this section, the biasedness is quantitatively evaluated. Scatter plots of speed difference data (loop detector speed – ETC speed) versus ETC speed are examined in Figures 11-13 (a). For each figure, best fitted lines are estimated, and equations and R-squared values are annotated. The figures show the followings:

1) **High R-squared values** (0.9433, 0.8357, and 0.9204): The fitted lines well explain the data.
2) **Positive slopes**: Speed difference is positively correlated with the speed, signifying that speed difference between loop detector and ETC measurements increases as speed increases.
3) **The fitted lines traverse zero speed difference** (x-intercepts are 90.0, 84.8, and 79.2): Below the speeds (at low speeds), loop detector speeds are faster than ETC speeds.
4) **Slopes** (0.5455, 0.5404, and 0.4419): Slopes mean the rate of changes in speed difference according to those in speed. Therefore, the slope estimates indicate 0.44~0.54 kph increase in speed difference per increase in 1-kph speed.

Figures 11-13 (b) are box plots that represent the non-parametric distribution of scatter plots in Figure 11-13 (a). The box plots show that the scatter data are neither skewed nor plagued by heteroscedasticity.

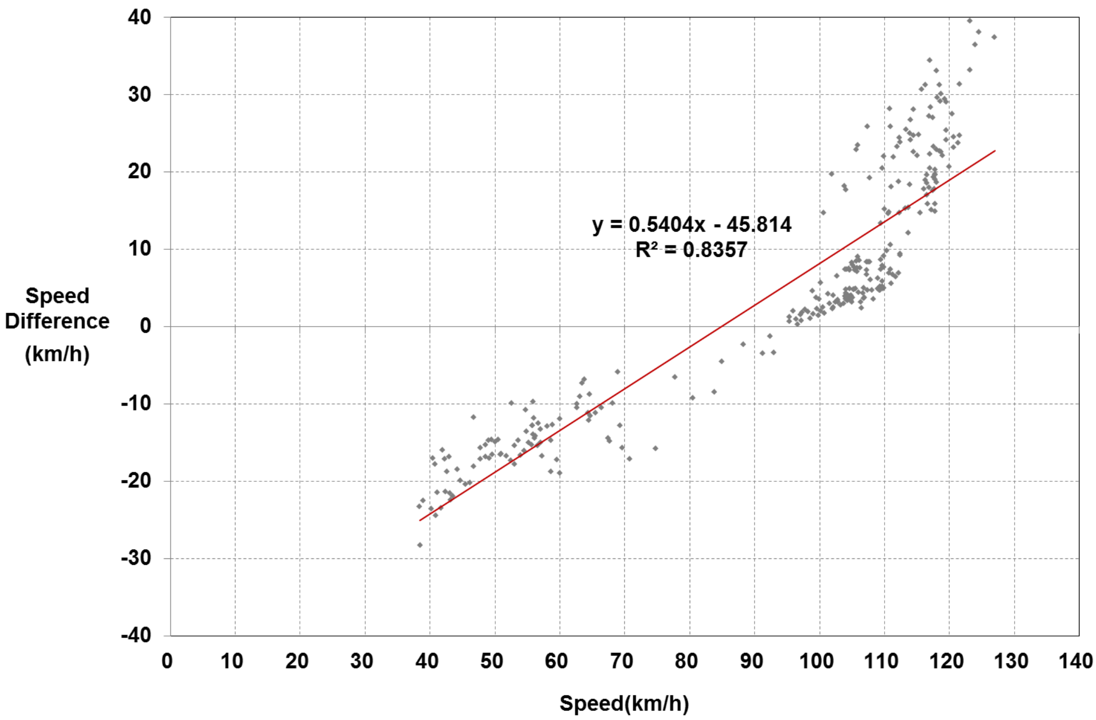


(a)

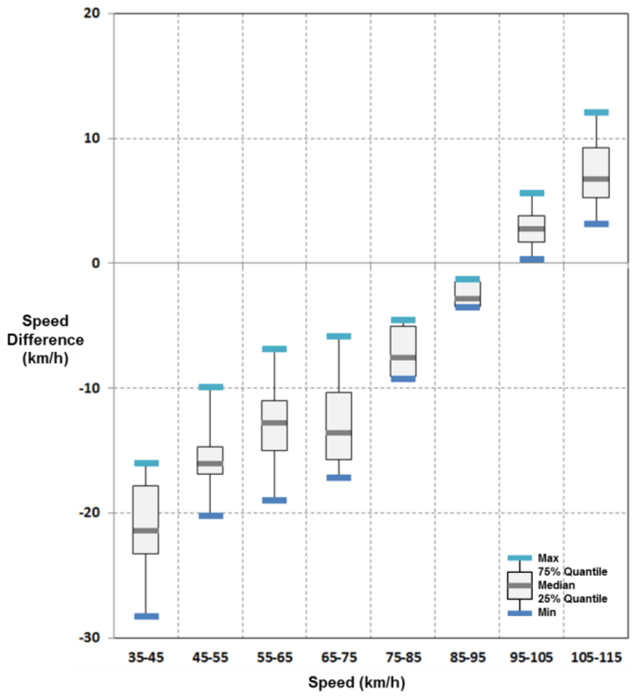


(b)

Figure 11 Speed versus speed difference; (a) scatter plots with the best fitted line; and (b) box plots (April 14th, 2011)

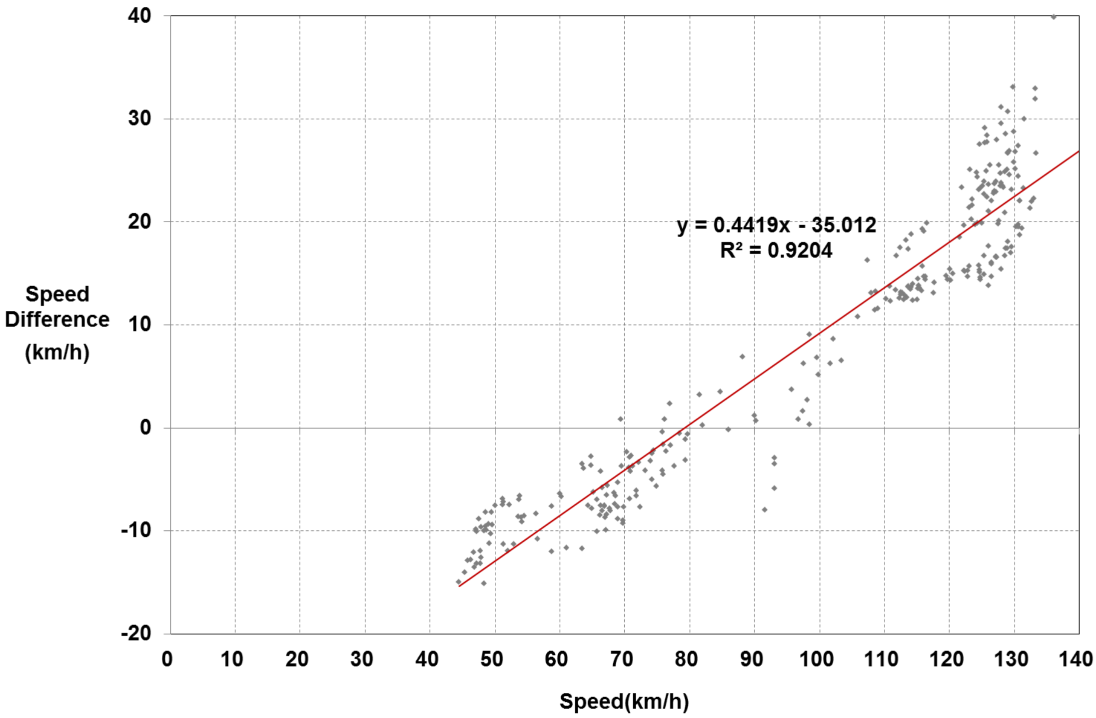


(a)

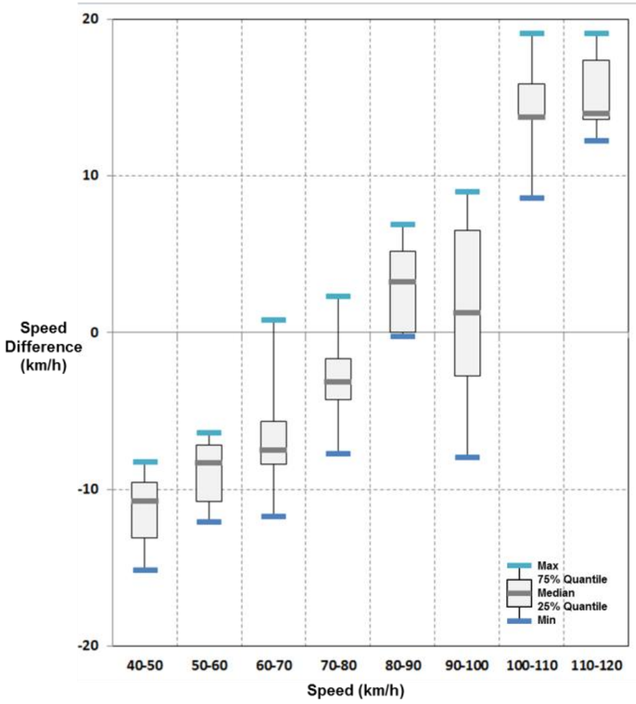


(b)

Figure 12 Speed versus speed difference; (a) scatter plots with the best fitted line; and (b) box plots (April 15th, 2011)



(a)



(b)

Figure 13 Speed versus speed difference; (a) scatter plots with the best fitted line; and (b) box plots (April 17th, 2011)

5. CONCLUSION

This paper examines speed data measured by two different sensing methods – loop detectors and ETC transponders. The former is based on the measurements at fixed locations while the latter measures actual travel time between RSEs. One-week of traffic data from 26.4-km section of Gyeongbu expressway in South Korea are analyzed. The analysis shows that speed measurements from loop detectors are higher at low speed conditions than those from ETC transponders. This biasedness is systematic such that an equation describing the relation between speed measurements of loop detectors and ETC transponders can be estimated. The estimated equation provides a promising tool that can be used to calibrate speed measurements from loop detectors.

This paper provides the quantitative insights on the speed measurements that are intrinsically different in the sensing mechanism. However, the findings documented in the paper are only based on the observations of one-week of data and may be case-specific. Further analysis with more detailed analysis based on full trajectory data such as NGSIM trajectories (NGSIM) should be conducted for validation. This analysis is now being conducted by the authors and the forthcoming paper will document the findings.

ACKNOWLEGEMENT

This research was supported by a grant (12 Transportation System - Intelligence 01) from Implementation of More Efficient Transportation System program funded by Ministry of Land, Transport and Maritime Affairs of Korean government.”

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