Understanding Intercity Freeway Traffic Variability at Holidays Using Anonymous Cell Phone Data

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Abstract. Due to the high market penetration of cell phones, the detailed spatial data offer new opportunities for sophisticated applications in traffic monitoring. Previous studies and projects have mainly focused on obtaining location and traffic estimations of individuals using data derived from cell phone networks. Understanding the variability of traffic patterns and congestion characteristics of intercity freeway systems caused by holiday traffic is beneficial, because appropriate countermeasures for congestion mitigation can be prepared and drivers can change their holiday travel schedules accordingly. This study collected 12 months of cell phone data and radar data along a highway in China. The traffic pattern during the Labor Day holiday in 2014 is investigated using the cell phone sample and speed data. The results have the potential to improve freeway operational performance during holiday periods.

Keywords: Intercity freeway · Holiday traffic · Anonymous cell phone data

1 Introduction

As wireless location technology is progressing very quickly, cellular probe technology is becoming a hot topic in the field of traffic engineering. Since cell phones move with people and vehicles, a huge amount of data can be collected at the individual level for estimating traffic-related parameters. Many studies have explored the use of cell phone data to estimate traffic states. Intuitively, monitoring and tracking the movement of cell phones within one wireless network can generate real-time estimated traffic states of the corresponding roadway network covered by the wireless network. For example, measuring the 'speed' of cell phones provides the scope to determine the speed of the vehicles. In past years, a number of simulated studies and field tests have investigated the feasibility of designing and developing a cellular probe-based traffic speed estimation system. Unlike other traffic sensing systems, these techniques rely on the location of the cellular phone over the time period, calibrated using triangulation of the GSM (Global System for Mobile communication) signal strength [1] over time; fingerprint matching of the phone's successive signal strength readings [2]; or the location of the cellular phone handoff between towers [3, 4].

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Several studies have evaluated traffic patterns using cell phone call data [5–7]. Holiday periods contributed to a large portion of traffic variability (i.e., different traffic congestion patterns in comparison with non-holiday periods) [8, 9]. However, the traffic patterns of the intercity freeway during special holidays have been rarely investigated. Among various statutory holidays in China, the National Day and Labor Day holiday periods were the busiest long-distance travel periods. Heavy traffic congestion and longer delay times are easily created on intercity freeway systems during holiday periods. An understanding of this substantial variation in traffic volume and speed due to holiday events is important for transportation agencies to establish appropriate holiday traffic management plans.

This study evaluates the change in traffic patterns caused by holiday traffic, and discusses how traffic patterns vary each day during holiday periods (before the holiday, during the holiday, and after the holiday). It is anticipated that the findings of this study will help transportation engineers and program managers implement appropriate congestion-related countermeasures for mitigating heavy congestion on a subject roadway during the busiest holiday periods. Drivers can also choose to avoid the congestion and change their holiday travel schedules based on the information about holiday traffic.

2 Literature Review

Based on information from the Bureau of Transportation Statistics, among various statutory holidays in the United States, the Thanksgiving and Christmas/New Year's holiday periods were the busiest long-distance travel periods of the year in 2001 [10]. This report showed that the number of long-distance trips increased by 54 % and by 23 % during the six-day Thanksgiving period and during the Christmas/New Year's holiday period, respectively.

Liu and Sharma analyzed twenty-year data collected by permanent traffic counters on highways in Alberta, Canada. The results of the nonparametric Wilcoxon matched pair test and Friedman method revealed that holidays substantially contributed to the variability of traffic [11]. Later, they showed that the strong directional features of holidays' effects. At the beginning of holiday periods, the volume increases were usually significant at a 95 % confidence level in the outbound direction, as this direction served the traffic from the population center (production area) to the recreation area (attraction area). At the end of holiday periods, significant volume changes were generally observed in the inbound direction, as this direction mainly carried the returning traffic from the attraction area to the production area [9]. Jun investigated the variability of speed patterns and congestion characteristics of interstate freeway systems during holidays. The estimated Gaussian mixture speed distribution showed the potential of improving freeway operational performance evaluation schemes for holiday periods [12].

Several studies investigated using cell phone call data to monitor the traffic speed. In 2003, a researcher from INRETS cooperated with researchers from the University of

California Berkeley to implement a field test on two freeway segments, and the report shows that, comparing the cellular probe data and the loop detector data, little variation occurred within the 32 km freeway segment, while a large variation was observed for the 4 km freeway segment [13]. Smith et al. compared speed estimation of cellular phone–based data with it of a point video sensor for 39 intervals of 10 min (min) each at different freeway locations, and for 35 intervals of 10 min each at different arterial locations. For arterial locations, the average absolute differences between the two measurement methods were 6.8 mph; for freeway locations, those were 7.2–9.2 mph [14]. Steenbruggen et al. reviewed systematically the main studies and projects addressing the use of data derived from mobile phone networks to obtain location and traffic estimations of individuals. They gave several general conclusions: (1) the most studied estimation issues for traffic management purposes were travel speed and travel time; (2) most of the studies focused on stretches of roads, or loops, and not on a road network level; (3) recent studies show more promising results [4].

3 Collection and Characteristics

The studied freeway is the G60 (Shanghai–Kunming Freeway) in China, which starts from Shanghai and ends at Kunming, Yunnan Province, a city that is 2730 km away, southwest of Shanghai. The studied section starts from Hangzhou and ends at Quzhou, as shown in Fig. 1. There are three other big cities along this freeway section: Zhuji, Yiwu, and Jinhua. The analysis is based on cell phone call data from December of 2013 to May of 2014. The information about these five cities is as follows:

- Hangzhou is the largest city of Zhejiang Province in Eastern China. It is the fourth largest metropolitan area in China. During the 2010 Chinese census, the metropolitan area held 21.102 million people over an area of 34,585 km^2.
- Zhuji is a county-level city, located about 40 miles south of Hangzhou. It spans 2,311 km^2 with a population of 1,157,938 inhabitants, according to the 2010 census.
- Yiwu is a city of about 1.2 million people in central Zhejiang province, according to the 2010 census. The city is famous for its small commodity trade and vibrant market, and is a regional tourist destination.
- Jinhua is a prefecture-level city. Its population was 5,361,572, based on the 2010 census, including 1,077,245 in the metro area.
- Quzhou is a prefecture-level city. As of 2010, its municipality registered a population of 2,413,500.

Figure 2 shows the sample number of the corridor on April 26, 28, 29, 30, and May 01 and 04. As May 01 to May 03 is a national holiday, we can see an obvious increase in the sample size on April 30 and May 01. More samples exist for southbound than northbound.

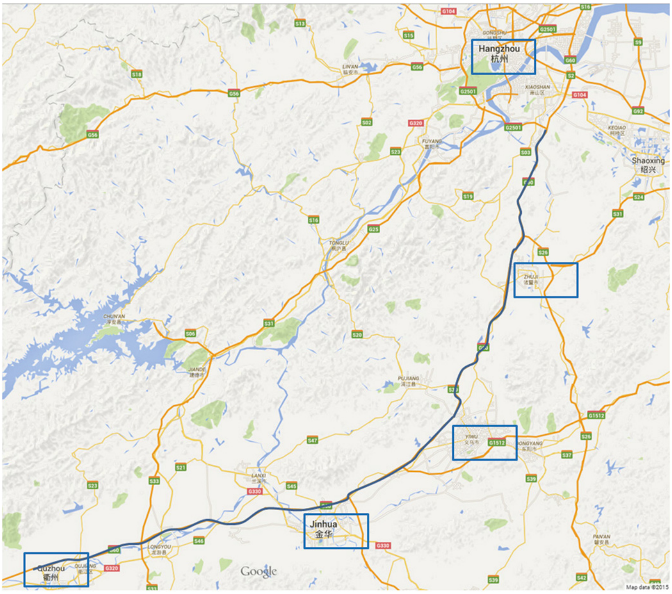

Fig. 1. Schematic diagram of studied freeway section

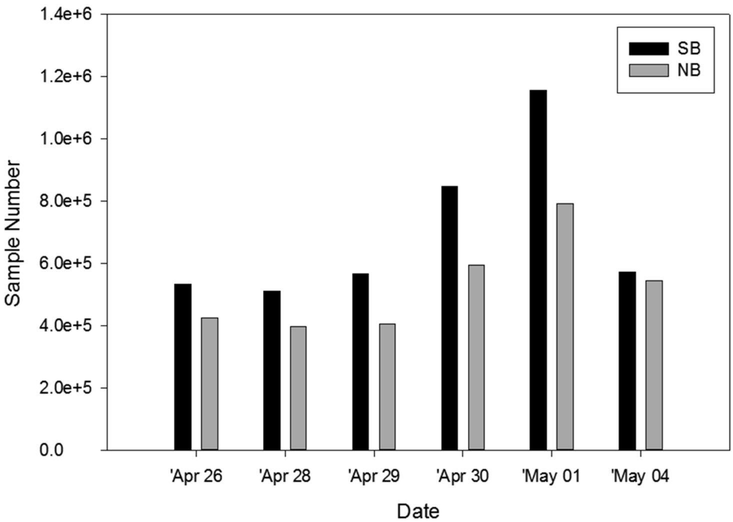

Fig. 2. Sample numbers for different dates

4 Speed Estimation Methodology

Figure 3 shows the system structure of a standard cellular network. A cellular network is a radio network made up of a number of radio cells, each served by a fixed transmitter, known as a base transceiver station (BTS), which is also termed a cell. These cells are used to cover different areas in order to provide radio coverage over an area broader than one cell. Cellular networks are inherently asymmetric with a set of fixed main transceivers each serving a cell and a set of distributed transceivers that provide services to the network's users.

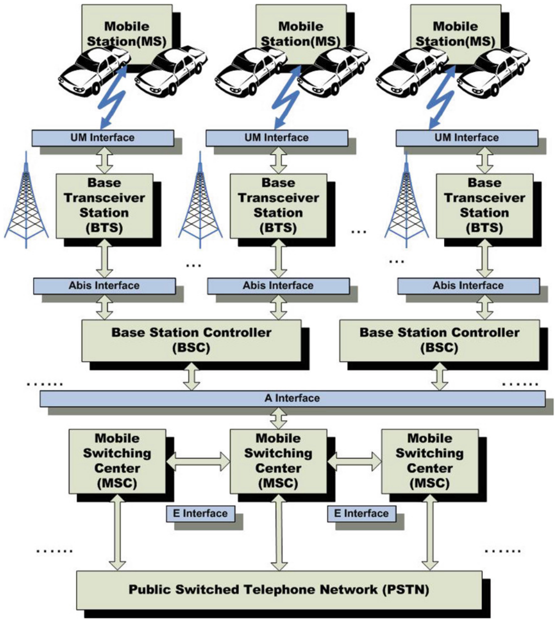

Fig. 3. Architecture of the cellular network

BTSs (cells) are all interconnected, which is the reason why someone can move from one cell to another without losing connection. BTS is the basic geographic unit of a cellular network system, and a city or county is divided into smaller cells, each of which is equipped with a low-powered BTS. The cells can vary in size depending upon the location, terrain and capacity demands, and the size can be several hundred meters or several kilometers. When a cell phone during a call moves from one cell toward another, a base station controller (BSC) monitors the movement, and at the appropriate time, transfers or hands off the phone call to the new cell. Handoff (HO) is the process by which the controller passes a cell phone conversation from one cell to another.

The handoff is performed so quickly that users usually never notice, and the controller records each handoff once it occurs.

Location update (LU) strategy is another mechanism for locating cell phones in the GSM cellular network, and it can handle all cell phones that have been turned on and are in idle status (not on-call). All the cells within the GSM network are grouped into a number of disjointed location areas (LA).

As shown in Fig. 4, a long road segment can be modeled as a straight line, divided into several smaller sections that are connected one by one and separated by the virtual sensor node, and the small segment determined by two consecutive handoff points is defined as a handoff link if and only if there exists one actual roadway link that can connect these two handoff nodes directly.

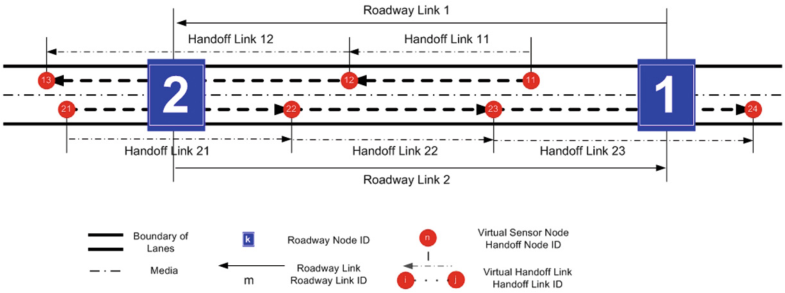

Fig. 4. Calibrated handoff points and two-way roadway links

Considering the projection relation between the roadway link and handoff link, there exist three cases:

- The two handoff points of handoff links are within the corresponding roadway link, and the roadway link is longer than the handoff link. For example, refer to handoff link 11 of roadway link 1 in Fig. 4.
- The two handoff points are placed on two sides of one node of the roadway link. For example, see handoff link 21 and 23 of roadway link 2 in Fig. 4.
- The two handoff points are on two sides of the corresponding roadway link, and the roadway link is shorter than the handoff link.

Each virtual sensor link of the virtual sensor network can be described as follows:

$$(H_{from}, H_{to}) = ((ID_{sensor\_from}, Cell_{from\_from}, Cell_{from\_to}), (ID_{sensor\_to}, Cell_{to\_from}, Cell_{to\_to})) \quad (1)$$

The two consecutive handoffs caused by one same cell phone p are called a handoff pair $H^p_{AB} = (ID_{cellphone}, t_{event1}, cell_A, cell_B)$ and $H^p_{CD} = (ID_{cellphone}, t_{event2}, cell_C, cell_D)$, which can determine the unique handoff link, except in cases of a multi-deck bridge or closely parallel roads. It should be noted that $cell_B$ and $cell_C$ are likely the identical cell due to the continuity property of adjacent cells. Given four continuous cells *A, B, C, D*, if we get the measurement of a HO link from handset p, (H^p_{AB}, H^p_{CD}), where H^p_{AB} = (p, t_{AB}, A, B), H^p_{CD} = (p, t_{CD}, C, D), and $t_{CD} - t_{AB} > 0$, we can easily calculate the moving speed of handset p when traversing the handoff link or location update route identified by H^p_{AB} and H^p_{CD}.

$$v^i_{p0} = \frac{L_{AB-CD}}{t_{CD} - t_{AB}} \tag{2}$$

And then translate the average HO link speed into the average roadway link speed using the following equation, which integrates the link length adjustment factor α:

$$v^i_p = \alpha\left(H^P_{AB}, H^p_{CD}, l\left(H^P_{AB}, H^p_{CD}\right)\right) \times v^i_{p0} \tag{3}$$

$$v^i_p = \alpha\left(H^P_{AB}, H^p_{CD}, l\left(H^P_{AB}, H^p_{CD}\right)\right) \times \frac{L_{AB-CD}}{t_{CD} - t_{AB}} \tag{4}$$

where, $L_{AB\text{-}CD}$ is the length of the handoff link.

Meanwhile, the parameter α needs to be chosen in order to minimize the mean squared estimation error. It should be noted that α functions for both the handoff link ID and roadway link ID, so both the roadway link-based speed results and the corresponding HO link-based speed results need to be collected for calibrating the parameters.

5 Results Analysis

Figure 5 shows the temporal variation of the sample number during holidays. Firstly, traffic patterns on April 26, 28, and 29 have a very similar trend, which increases during morning and decreases during evening. Secondly, the sample number starts to increase significantly for April 30, and we can see a much higher sample number on May 01. The reason is that people drive to visit family and friends during the holiday. Thirdly, the increase of the southbound (SB) sample number is much larger than for northbound (NB) traffic, which means more people are traveling outside of Hangzhou to the other four southbound cities. The data clearly show substantial holiday effects on traffic volumes, and the effects are different for outbound and inbound directions.

Figure 6 shows the speed dynamic at one location from April 21 to May 07. The speeds detected by the cell phone and microwave vehicle detector have the same identical trend during holidays, weekends, and weekdays. We can see a clear speed drop on May 01 due to higher traffic volume, especially during the morning.

For further analysis, Fig. 7 shows the speed contour along the studied corridor for May 1. There are obvious congested links and time intervals along the corridor. The northbound and southbound directions show different traffic dynamics. We can see one significant SB congestion in the early morning, at about 3:30 AM.

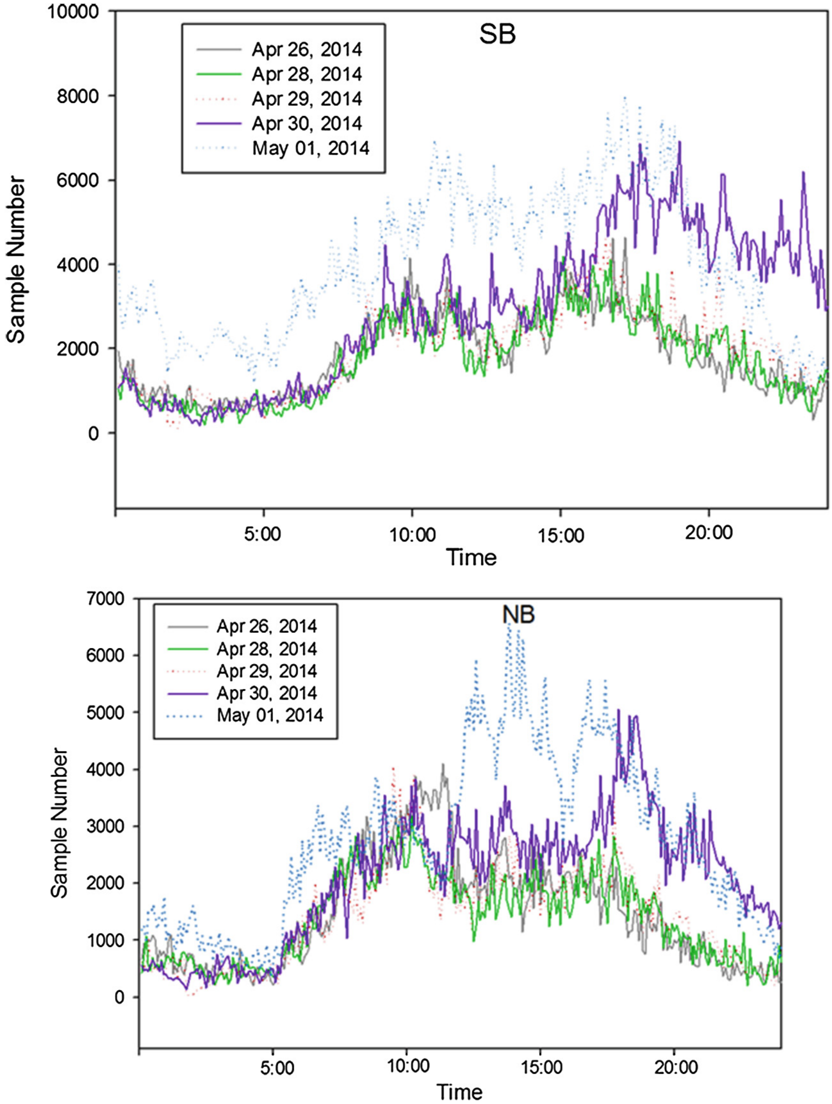

Fig. 5. Temporal variation of the sample number during holidays (Color figure online)

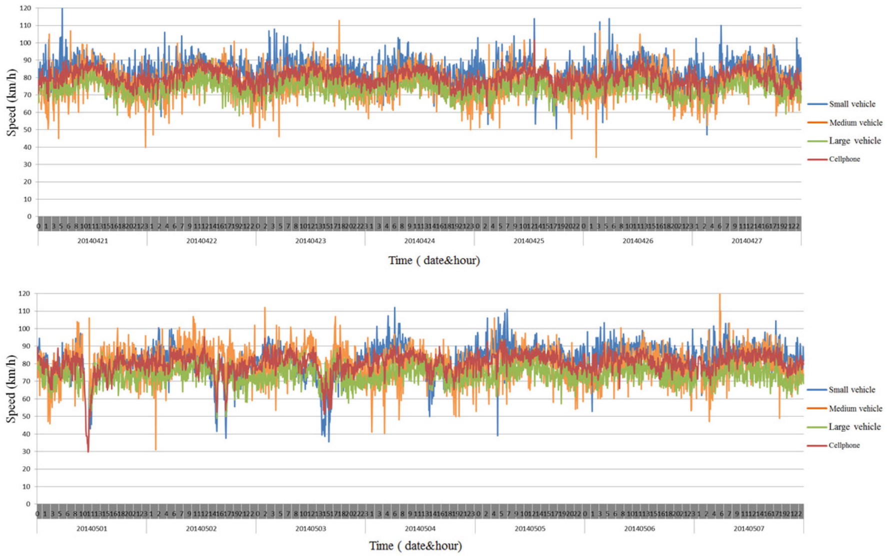

Fig. 6. Speeds (km/h) at one location from April 21 to May 07 (Color figure online)

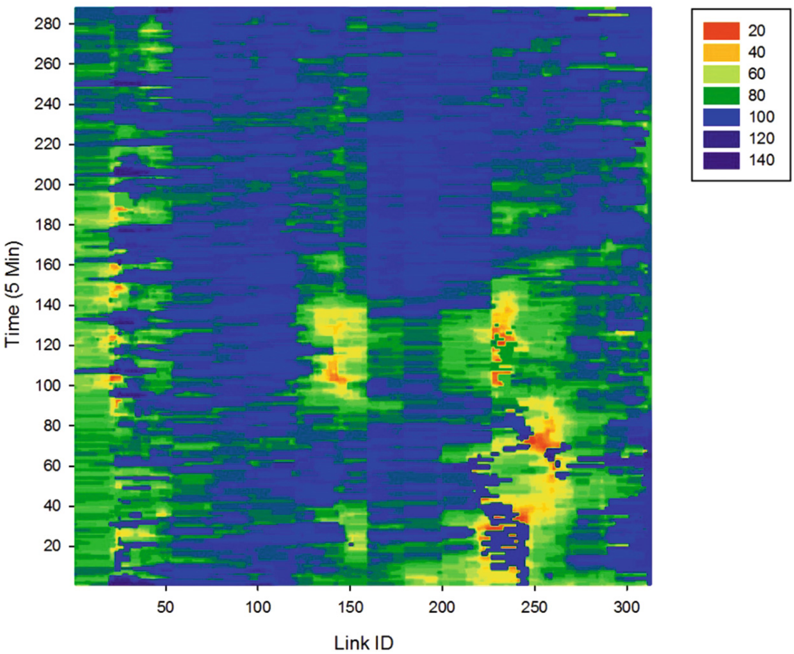

Fig. 7. Speed (km/h) contour along the southbound corridor on May 01, 2014 (Color figure online)

6 Conclusions

Recent studies have showed promising results of using mobile phone data for sophisticated applications in traffic management and monitoring. This study uses the cell phone call data to investigate the effects of holidays (observed in Zhejiang, China) on traffic patterns. Results show that holiday affects daily and hourly traffic volume and speed, and the effects are different for southbound and northbound directions. A good understanding of temporal and spatial traffic patterns due to holiday effects can assist in developing appropriate countermeasures for congestion mitigation. The next phases of the research will include the development of speed distribution model to investigate the trends of speed patterns and congestion characteristics.

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