Traffic Flow Analysis by the Use of Wi-Fi Packets Receiver

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There has been sharp increase of mobile communication terminals such as smartphones and tablet computers with Wi-Fi function in use. When a smartphone performs packet communication, it transmits a unique ID number of the device at regular intervals even in standby mode, so it is possible to track the movement of mobile bodies by receiving packets at multiple locations on roadsides and analyzing them.

This paper shows the results of experiments analyzing traffic and person flows by the use of Wi-Fi packet receiver which was uniquely developed by the authors. The authors measure traffic flows on an expressway and ordinary road and calculate travel time both in Japan and abroad. Person flows at a service area on expressway and a fast-food restaurant in an urban area are also measured in order to analyze residence time and usage situation of the facilities.

The possibility of further applications to the breakdown of traffic-flow and/or low-cost Origin-Destination surveys by additional allocation of sensors in wider areas will be also discussed in the paper. The traffic-flow analysis using Wi-Fi packet data from smartphones should be more beneficial especially in developing countries with insufficient traffic-flow observation systems.

Key Words : *system analysis, travel behavior survey, road planning, public transport planning, traffic information, ITS*

1. Research Objectives and background

Due to the rapid dissemination of smartphones in recent years, many mobile bodies have become equipped with communications terminals that have Wi-Fi functionality. Since many smartphones transmit a type of Wi-Fi packet that includes a unique ID number for the device, by receiving and analyzing these packets, it is possible to ascertain the traffic flow of a broad range of mobile bodies.

By receiving Wi-Fi packets on roadside and comparing data at multiple locations, it is possible to measure the movement speed over distances (travel speed) of automobiles and people at extremely low cost. Furthermore, if we measure the start and end time of Wi-Fi packets that are continuously observed at the same location, we can measure residence time of people and automobiles.

These traffic flow sensors that can easily observe traffic flows from the side of the road could be utilized in many regions. In particular, they hold much promise for practical use in developing countries, where the facilities for traffic flow measurement infrastructure are insufficient.

In the past few years, a variety of approaches and research for implementing analysis methods of traffic flow through the acquisition of unique wireless packet information have been carried out in many places. However, many of these use Bluetooth, and not much research on Wi-Fi packets has accumulated. Moreover, in order to measure traffic flow by acquiring unique wireless packet information, we must use a method that pays the utmost care to protection of personal privacy, or else even if all of the technical problems were resolved, it would be difficult to gain the understanding of the public.

We developed the hardware and software for using Wi-Fi packet sensors to analyze traffic flow, applied them in multiple fields, and took many measurements. In addition to capable of measuring traffic flow of vehicles on expressways and ordinary roads, we were able to confirm that the Wi-Fi packet sensors could be effective as sensors to ascertain the flow of people in congested areas such as service areas and metropolitan areas. Moreover, making the acquired data anonymous and conforming to personal information protection laws is indispensable. We consider measures to delete the data from users who do not wish to be acquired (in other words, an “opt-out” method), and propose a method of operating the sensors in a way that does not cause any legal or socio-ethical problems.

2. Wi-Fi Packet Receiver

In recent years, mobile information devices with Wi-Fi communication functionality have rapidly disseminated. The terminal with the highest rate of dissemination is the smartphone, but other devices, from notebook PCs to mobile gaming devices and recently even digital cameras, are also outfitted with Wi-Fi communication functionality.

Most of these devices transmit management packets, called "Probe Request Packets," that search for Wi-Fi routers to connect to even in standby mode. There is some discrepancy between the frequency at which different devices transmit this signal, but most generally transmit them at intervals of around 30 to 90 seconds. Since this packet includes a device-specific address assigned to each device (a MAC address), by comparing the MAC addresses of packets acquired by sensors in multiple locations, we can analyze many types of traffic flows.

It is not possible to identify an individual solely based on the unique device information included in the packet. If, however, one were to obtain the MAC address of an individual and maliciously connect it to the person's personal information, it would be possible to track that individual's activity. So we convert the acquired MAC address inside the sensor through a one-way hash function so that the analysis can be processed anonymously.

We call this sensor, which receives Probe Requests with anonymous MAC addresses, the Anonymous MAC address Probe sensor, or AMP.

3. Literature Review

(1) Traffic Flow Analysis using Bluetooth packets

It is possible to measure travel speed of automobiles by receiving packets transmitted from Bluetooth devices in automobiles and comparing them with MAC addresses as identifiers. Much traffic flow analysis research using this method has been presented since 2010, particularly abroad. Trung Vo[1)] used this method to measure travel speed of automobiles on trunk roads. Compared to measurement methods using license plate identification, magnetic sensors or RFID tags, the measurements were effective with respect to accuracy, cost superiority, and anonymity. He has conducted various other researches[2)] on analysis of traffic flow with this method.

In Japan, Kitazawa and Shiomi have attempted research[2)] to measure travel speed on the Hanshin Expressway, and they succeeded at measuring travel speed by comparing the MAC addresses of packets transmitted via Bluetooth measured at two points on the Hanshin Expressway.

(2) Traffic Flow Analysis using Wi-Fi packets

Compared to analysis of traffic flow using Bluetooth, there is little research on analysis of traffic flow using Wi-Fi packets.

Luber Andreas et al. compared measurements of travel speed on roads using Bluetooth and Wi-Fi and conducted research[4)] to reevaluate the superiority of each. However, upon setting up Wi-Fi and Bluetooth wireless devices on roadside gantry and comparing the detection of each, they found 6.5% detection of Bluetooth and only 1% detection of Wi-Fi, leading to the conclusion that Bluetooth was favorable. However, in fields other than roads, there is research[5)] by Ryusuke Nakano and others on approximating the degree of crowding inside train cars by attempting to estimate the number of passengers inside the cars using probe request receivers installed inside the cars.

(3) Comparison of Bluetooth and Wi-Fi System

As stated above, based on the existing research, there are many examples concluding that measurements by Bluetooth are more favorable than those by Wi-Fi.

The reason for this is that with Bluetooth measurements, first the sensor transmits an API connection request (a request for coupling), waits for the other terminal to respond, and then acquires the MAC address included in the reply from the other device, so acquisition of the other device's MAC address is simple. Furthermore, we can infer that since the dissemination of Bluetooth preceded Wi-Fi for transmission for devices inside automobiles, such as mobile telephone headsets and devices to connect to the sound system, the result of the measurement was that the rate of detection of Wi-Fi was higher than that of Wi-Fi.

However, in analyzing traffic flow on expressways, when measuring with Bluetooth, it takes a certain amount of time (8 – 13 seconds) between transmitting the connection request and reply from the device. So during that time the automobile may leave the sensor's effective range and it has been pointed out[5)] in detection of high-speed vehicles, the detection rate drops. In the aforementioned research by Kitazawa et al.[3)] , the number of MAC addresses detected at both points on the Hanshin Expressway in Japan was quite small, at only 2 – 17 in a 2 hour interval. A cause of this was, in addition to the response time for coupling, the problem of the wave strength approved for Bluetooth. Namely, in other countries the wave strength approved for Bluetooth is 100mW, but in the Japanese Radio Law only half that strength, 50mW, is approved.

On the other hand, the recent rapid dissemination of smartphones has drastically increased the number of automobiles with Wi-Fi devices in a short time. In an article in ITS World presented at approximately the same time as our research introducing the measurement results[7)] of Blip Systems A/S from the Netherlands, it was reported that although previously the detection rate for Bluetooth was clearly higher, recently the detection rate for Wi-Fi has exceeded that of Bluetooth.

It is not a matter of whether to use detection by Bluetooth and detection by Wi-Fi, but by using a hybrid sensor that responds to both types of signals, it is possible to analyze traffic flow with a higher detection rate. Blip Systems A/S of the Netherlands already developed[7)] a sensor that measures both types simultaneously.

4. Organization of the System

To develop the AMP sensor, we aimed to make it easily installed in a variety of environments and developed the following two items.

A. Development of sensor software that could be operated on general -purpose PCs

B. Development of low-cost, small sensor hardware

(1) Development of Sensor Software Operated with General PC

We have completed development of sensor software that operates on three different operating systems (OS), Macintosh, Windows, and Linux.

The structure of the AMP sensor software is described in Fig. 1. After capturing the Wi-Fi packet, it is immediately hashed with SHA-1 and after storing the acquired log on the internal memory, it is uploaded to cloud storage server each designated period of time.

The time for each sensor is synchronized with NTP, so since the timestamps of multiple AMP sensors are synchronized, it is possible to accurately measure speed with the data from AMP sensors between multiple points.

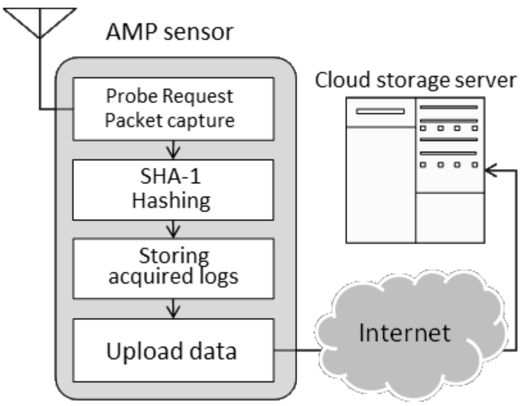

Fig. 1 Structure of the AMP Sensor System

(2) Development of Affordable and Small Sensor Hardware

We used hardware, Raspberry PI Model B. The CPU is an ARM 1176JZF-S 700MHz. The storage is SDRAM 512MB. The cabled connection is a 10/100 BaseT Ethernet socket in the main unit, which uses USB wireless LAN adapter connected via USB 2.0 for wireless signals. It consumes 3.5W of electricity, and the OS is the Linux-based Raspbian 3.6.1+.

When the unit is connected to the Internet, such as via Ethernet cable, it automatically uploads the recorded data to a cloud storage server. However, when it is set up autonomously, it records its log on an SD card and can operate continuously for about one month. Furthermore, in order to equip it with UPS function (Uninterruptible Power Supply), when operating on a mobile battery, it can function for approximately 3 hours even without electricity.

The unit was intended to be installed indoors. Thus, in order to set up outdoors, it needs to be produced and take into consideration of temperature changes and weather resistance such as using industrial circuit board.

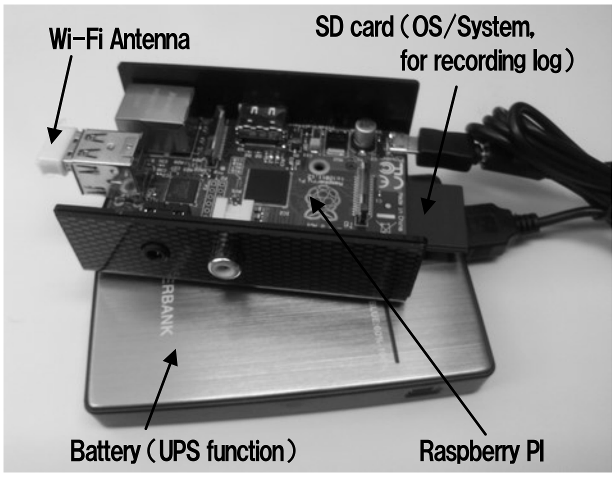

Fig. 2 Structure of the AMP Sensor Hardware

(3) Cloud Storage Server

The West Nippon Expressway Company Ltd. (NEXCO-West) has cloud storage servers that can be accessed via the Internet for the purpose of collecting, analyzing, and servicing a large amount of probe data. It is simple to scale up this cloud storage server by increasing the amount of data, and it has a distributed database processing engine that can process large quantities of data.

The collected data transmitted from the AMP sensor records the SHA-1 hashed MAC address, time received, and signal strength in a single line and stores the acquired log on the server each designated period of time. The amount of data transmitted from one AMP sensor is not large, but in the future, in order to smoothly process data if many AMP sensors are set up and continuously operated, we developed the environment capable to use NEXCO West's high-powered cloud storage server.

The data uploaded to the server is immediately aggregated by the analysis system, and from the difference in time between the observations of the same ID measured at two designated locations, the distribution of travel speed for each designated period between each section is calculated.

(4) Wi-Fi Packets Accessible Distance

Using the system explained in (1) - (3), we conducted various functionality tests of the AMP sensor operation and data processing. The Wi-Fi probe packets had the quite significant travel distance of 200 – 350m. However we measured the signal strength of each packet, and it was possible to judge the distance using this signal strength (-35db ~ -95db). We have just begun to consider the possibility of structure that identifies location based on signal strength by installing multiple AMP sensors at designated distances, and it will be the subject of future research.

5. Traffic Flow Analysis on Roads

We measured travel speed on roads at following locations using either the AMP sensor we already developed or AMP sensor prototype under development.

A) Japan: Packet Acquisition test on National Route 163
Date/Time: Multiple days in April, 2013

B) Japan: Travel speed measurement on the Sanyo Expressway
Date/Time: July 5, 2013 11:50 - 12:50

C) Japan: Residence time measurement at Miki Service Area on the Sanyo Expressway
Date/Time: July 5, 2013 13:35 - 14:25

D) Japan: Travel speed measurement in Osaka
Date/Time: January 12, 2014 10:00 - 12:00

E) Indonesia: Travel speed measurement in Makassar
Date/Time: January 22, 2014

In this article, we will discuss the measurement results of the first test conducted, "B) Japan: Travel speed measurement on the Sanyo Expressway," as well as "E) Indonesia: Travel speed measurement in Makassar".

The measurement was conducted to monitor packets using MacBook Air, Linux notebook PC, etc. set next to a parked car on roadside (Fig. 4). For this reason, there were problems of bias in the packet acquisition according to driving direction. Since we did not set up a special antenna, the reception sensitivity was low as well.

Fig. 4 Scenes of the Experiment on the Sanyo Expressway

However, even though we employed this simple measurement method, as seen in **Table 1**, in 60 minutes of measurement we were able to acquire 134 samples on the Miki-Higashi side, and 139 on the Kakogawa side. We had 22 valid samples that were detected at both sites.

(1) Measuring Travel Speed of Section on Sanyo Expressway

At the beginning stage of development of the AMP sensor, using the sensor software developed for the internal Wi-Fi antenna in general-purpose PCs (Macintosh, MacBook Air, Linux PC), we installed the devices over an 11.4km interval on the Sanyo expressway between Miki-Higashi and Kakogawa and conducted test measurements to see if it would be possible to receive Wi-Fi packets from high-speed vehicles and to measure travel distances in that section by comparing MAC addresses.

Before this experiment, in the preliminary experiment conducted along the side of an ordinary road, we were able to confirm receipt of a certain number of unique IDs, but we conducted this experiment to confirm whether it would be possible to measure the travel speed of high-speed vehicles. The section measured in this experiment is shown in Fig. 3.

Fig. 3 Travel Speed Measurement Experiment on Sanyo Expressway

Table 2 shows the vehicle travel speed calculated using the acquired data. They almost match with the speed measured by the traffic counters installed in nearby locations shown in **Table 1**. Samples 20 – 22 had extremely slow speed of 19.1 – 45.6 km/h, but since there is a service area between these two points, it can be assumed that these vehicles stopped there. Suppose the average speed is 80 km/h, the amount of time spent at the Miki Service Area would be between 6 and 27 minutes.

Through this experiment, we were able to see that Wi-Fi packet sensing is well suited to the measurement of the travel speed of vehicles on expressways and ordinary roads.

Table 1 Acquired Packets on the Sanyo Expressway (60 minutes of measurement)

Location	Number of vehicle	Average speed in traveling lanes	Average speed in passing lanes	Acquired packets	Acquisition rate
Miki-higashi	1,092	87.0km/h	103.9km/h	134	12.20%
Kakogaw a	1,247	87.6km/h	105.4km/h	139	11.10%
		Commonly acquired packets		22	1.76%

Note) Number of vehicle and travel speed by lane: traffic near the observation point
Value measured with counter (provided by NEXCO-West)

Table 2 Travel Speed Calculated from the Acquired Data

Sample	Time difference (seconds)	Traveling speed (km/h)	Miki SA (minutes)
1	342.481	119.8	Time stayed at Miki service area assuming driving at average speed 80km/h (min.)
2	356.781	115	
3	369.128	111.2	
4	374.231	109.7	
5	395.383	103.8	
6	407.784	100.6	
7	408.896	100.4	
8	441.045	93.1	
9	443.945	92.4	
10	444.562	92.3	
11	447.322	91.7	
12	453.151	90.6	
13	458.658	89.5	
14	460.465	89.1	
15	484.484	84.7	
16	488.563	84	
17	494.112	83.1	
18	516.353	79.5	
19	525.361	78.1	
20	900.668	45.6	6.3
21	1,011.09	40.6	8.2
22	2,153.62	19.1	27.2

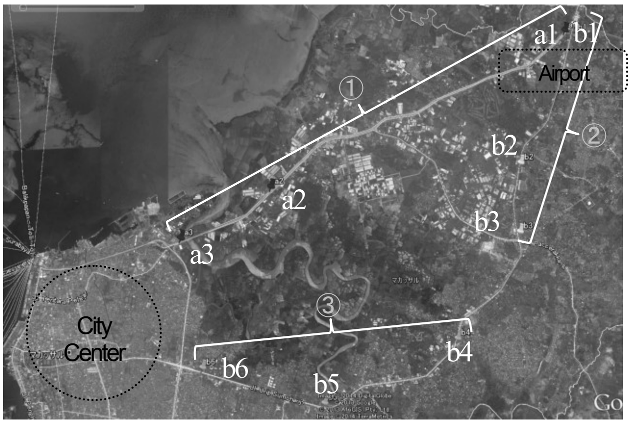

Fig. 5 Sections where Travel Speed was Measured in Makassar

Fig. 6 Scenes of Measurement at the Side of the Expressway (a3 Location)

(2) Measuring Travel Speed in Kota Makassar in Indonesia

Automotive traffic is rapidly increasing in developing countries such as Indonesia, but since there is insufficient infrastructure, such as traffic counters, to measure traffic flow, the traffic situation on the roads cannot be ascertained. For this reason, provision of information on route selection and expressway use is insufficient. Through introduction of ITS, we measured travel speed on Makassar's expressways and ordinary roads for the purpose of building a system to provide information on road and traffic status.

Fig. 5 shows the section s where traffic speed was measured on site. Section 1. is an expressway and section s 2. And 3. are ordinary roads that run alongside expressways. In all three section s, we installed measuring points at three sites, on both ends and in between them and took measurements.

There were frontage roads on the expressways measured, and there were both four-wheeled automobiles and two-wheeled motorcycles driving on the frontage road in the a1-a2 section. In particular, there were many section s of the frontage road in the a2-a3 section that were narrow and were only for two-wheeled vehicles. Two-wheeled vehicles (motorcycles) were not permitted on the trunk road of the expressway.

Since, as noted in 4(4), the traveling distance of the Wi-Fi packets was 200 – 350m, there was the problem that the AMP sensor set on the trunk road would measure the travel speed of vehicles driving on the frontage road as well.

Next we will explain the situation of section 2. Section 2 in Fig. 5 (measurement points b1, b2, and b3) is a trunk road from the airport to the city center. It is a trunk road with mostly one lane traveling in each direction, and there are commercial facilities alongside the road. Section 3 (measurement points b4, b5, and b6) is a trunk road with 2 or 3 lanes of traffic in either direction, but it is near the city center and there are many traffic jams mainly during peak hours in the morning and evening.

This means that on ordinary roads, measurements of travel speed would not be only of automobiles, but of bicycles and pedestrians as well.

Fig. 7 State of Traffic on Ordinary Road (b5-b6 Section)

Table 3 shows the results of measurements taken by the AMP sensor in sections 1 – 3.

Table 3 Measurement Results in Makassar

Sec-tion	Point	Number of vehicle during obser-vation	Observed number of unique ID	Observati on time (min.)	Number of unique ID per minute	Acquisi-tion ratio (%)	Observed number of unique ID at 2 points	Number of observed unique ID at 2 points per minute
High-way 1.	a1	2,025	143	90	1.6	7.1%	74	0.82
	a2	3,177	318		3.5	10.0%	94	1.04
	a3	3,258	173		1.9	5.3%		
Ordi-nary-East 2.	b1	4,512	158	60	2.6	3.5%	56	0.93
	b2	6,456	246		4.1	3.8%	83	1.38
	b3	5,898	217		3.6	3.7%		
Ordi-nary-East 3.	b4	12,738	471	60	7.9	3.7%	171	2.85
	b5	12,120	761		12.7	6.3%	217	3.62
	b6	13,794	459		7.7	3.3%		

*Unique ID is the number of unique ID included in Wi-Fi packet measured at each observation location. It matches the number of observed Wi-Fi devices.

*Number of vehicles on ordinary roads includes the number of two-wheelers (motorcycle).

* "a2" observation location is near the toll road exit, and vehicles tend to slow down.

* "b5" observation location is near a commercial complex.

Based on these results, we can see that the capture rate is low compared to the measurements in Japan in July, 2013 on the Sanyo Expressway. The number of IDs that was measured at two locations, and the number of observations that could be used to measure travel speed was average of 0.8 to 1.0 per minute on the expressway, and 0.9 to 3.6 per minute on ordinary roads. In a time period with similar levels of traffic, if setting the time units for travel speed measurement at 15 minutes, it is possible to acquire above average sample numbers in 15 minutes on both inbound and outbound routes on the expressway. Locally, the rate of dissemination of smartphones is increasing, so we expect that the accuracy of this measuring method of travel speed will improve in the future. Furthermore, as at location a2, near the tollbooth on expressways where drivers slow down, the capture rate improves. If we install sensors at these locations giving priority, the capture rate would increase further.

Next, we calculated the traveling time between two locations from the packets that could be measured at two points. At each measured section we looked for the distribution of travel speed. The measurement results for the a2-a3 section are shown in

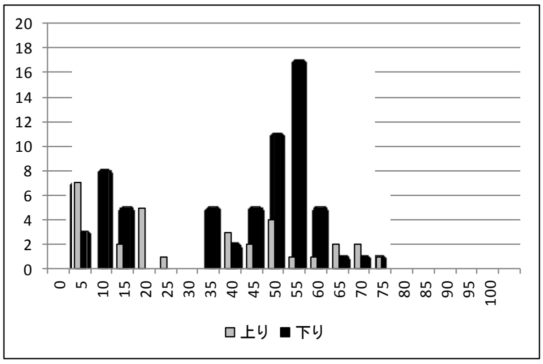

Fig. 8.

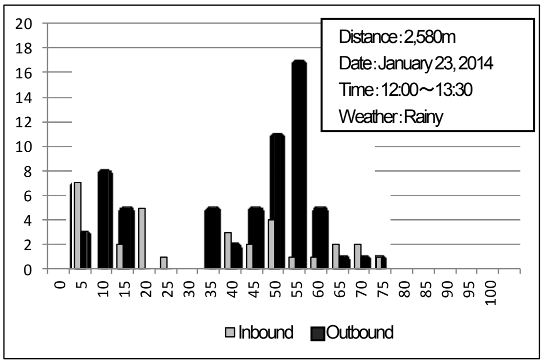

Fig. 8 Travel Speed Measurement Results on Expressway (a2-a3 Section)

The lighter bar shows the inbound route (from the airport into the city center), and the black bar shows the outbound route (from the city center to the airport). Overall, the reason that the number of observations of inbound vehicles was greater is thought to be because the observing vehicle was parked along the inbound side of the road to take measurements. We interpret the reason that the distribution is divided in two to be that the lower speed group was vehicles traveling on the frontage road, and the higher speed group was vehicles traveling on the expressway. As there was tropic squall about 10 minutes after beginning the measurements on the expressway, heavy vehicles that slip easily, such as container trucks lowered their speed. The reason that the speed distribution of vehicles diving on the expressway was wide, from 35 – 75 km/h, is due to the effects of the squall.

Next, the results of the b5-b6 section from among the travel speed measurements of the ordinary roads are shown in Fig. 9.

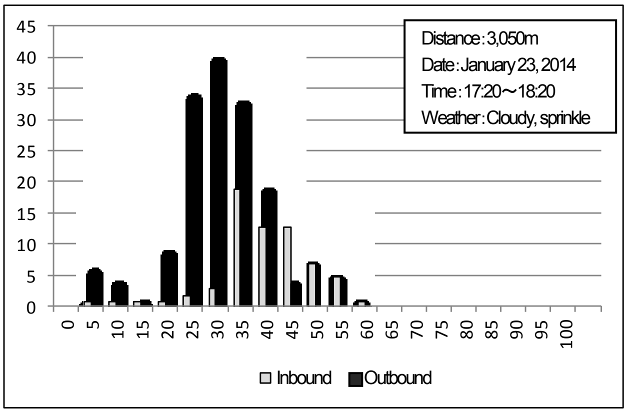

Fig. 9 Travel Speed Measurement Results on Ordinary Road (b5-b6 Section)

In Makassar, there are still few traffic lights on ordinary roads, and thus, the speed is high without traffic jams, 40 – 50 km/h. However, during rush hours, cars attempting to turn right stop the flow of oncoming traffic, and intense traffic results. The time when the measurements were taken overlapped with the evening rush hour, and especially on the outbound lane where people were returning home, a decrease in travel speed due to traffic was measured.

6. Residence Time Analysis

In the traffic flow analysis by the AMP sensor, in addition to analyzing travel speed between two points, by aggregating the time records when the same ID was measured continuously, it is possible to find distribution of residence time. On the expressway, it is effective in analyzing usage tendencies and residence time of service areas and parking areas.

We will next introduce an example of this residence time analysis.

(1) Distribution of residence time at the Miki Service Area

On the same date and time that we measured travel time on the Sanyo Expressway between Miki-Higashi and Kakogawa as explained in 5(1), we measured the residence time distribution at the food court in the Miki Service Area. The results of these measurements are shown in Fig. 10.

The food court at the Miki Service Area is located next to retail stores but is distant from restaurant and toilet. In these results, we see that during the 50 minutes that measurements were taken, we measured about 60 samples. Here, we defined delays as those samples measured continuously for over one minute. Samples that did not stay inside the building and just passed through in front of the buildings were excluded.

Since we started at 13:35, after lunchtime, but we observed many people eating at the service area. However, we also observed many who purchased drinks from vending machines, browsed quickly through the store, and left. The results in Fig. 10 show that many of the users during the time at the service area facility were there for only a short period of time.

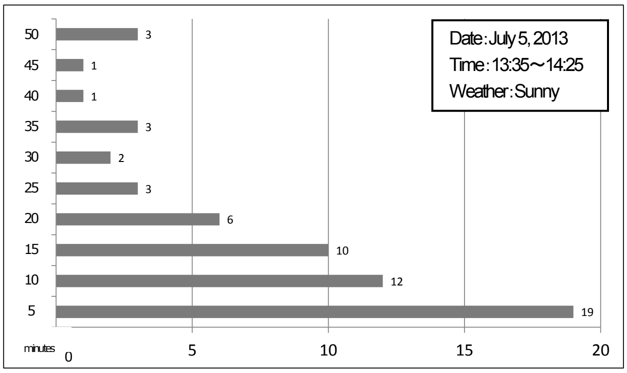

Fig. 10 Distribution of Residence Time at Miki Service Area

(2) Distribution of residence time at fast food restaurant in front of the train station

This example of analysis is not related to roads, but with the cooperation of a fast food restaurant in front of the train station, we took continuous measurements over the course of 17 days. We are unable to publicize the name of the restaurant and the date and time measurements were taken, but are able to use the measurement data taken exclusively for academic purposes.

the number of customers at the point-of-service (POS) registers and the number of AMP sensor measurements for five of those 17 days including a weekend. Based on these results, we can see that the number of customers counted at the POS registers in the fast food restaurant in front of the station matches accurately the number of customers staying in the restaurant measured by the AMP sensor. The correlation coefficient between these two numbers was 0.945.

There were some discrepancies, depending on the hour, between the number of customers at the POS registers and the numbers measured by the AMP sensor; the numbers for customers at the POS registers is higher during lunchtime on weekdays, and the numbers observed with the AMP sensor were higher in the evenings. As this restaurant locates in suburb, there were many groups of middle-aged housewives during the day, and there were many students and businessmen in the evenings. Therefore, we infer that the difference in ownership rate of smartphones among customer types and the hours affected the results.

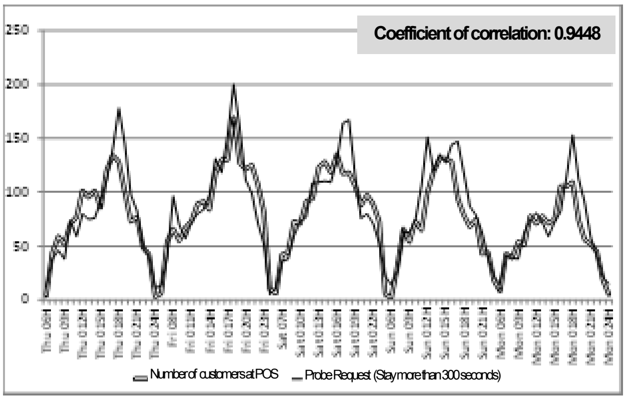

Fig. 11 Number of POS Registers and Numbers Observed by AMP Sensor at Fast Food Restaurant in Front of the Station

7. Sensing and Personal Information Protection

In the AMP sensor system, we took the utmost care to protect personal information; the measured MAC addresses were made anonymous using hashing function, and the coding and hacking countermeasures on the server were set at high level.

The information acquired with this system is not categorized as personal information stipulated under the Japanese Personal Information Protection Law, but it has characteristic of personal data that can be used to recognize individual's behavior. Currently in Japan, there will be amendment of the Personal Information Protection Law, and a bill will be submitted in 2015. In advance of the amendment, in December 2013, the "Policy Outline of the Institutional Revision for Utilization of Personal Data"[8] related to personal data protection was publicized. Following this policy outline, we developed principle on the system taking the following measures:

1. Define the purpose of use for data collected
2. Define the content of data collected and how it is to be handled
3. Define prevention measures for those who do not wish to be observed (such as by turning off the Wi-Fi functionality on their smartphone)
4. Define the contact information for deleting data if anyone's personal data was obtained against their wishes, and preparation method for handling (opt-out measures)
5. Set a period of data storage for analysis, and clearly state to not disclosing data to any third parties

If measurements were to be taken in small area, the above 1. to 5. could be posted around the sensor, etc. If it is wide area, they could be posted on website or issued a press release. It would be necessary to publicize the information with appropriate methods.

8. Conclusion

In this article, we described the sensor software and hardware to conduct analysis of traffic flow by sensing Wi-Fi packets from smartphones, etc. that have been disseminated rapidly in recent years. We also showed applications in measuring travel speed and residence time analysis. The AMP sensor we developed shows high potential to be used for analysis of traffic flow in vehicles on roads including expressways, and people flow. Furthermore, we proposed measures to protect personal information and personal data, which are both legal and ethical concerns once the system is implemented in practice.

Wi-Fi packet sensors are a measurement method that has become practical rapidly in the past one to two years. We expect that it can be used widely in society.

In the future, we hope to continue with not only analyzing travel speed and residence time at a few locations as in this article, but also by installing numerous sensors widely, we hope to continue with systems to examine wide-area traffic flow and applications for Origin-Destination surveys at low cost and so on. Moreover, we hope to further research in various fields, such as disaster planning and operations management of urban facilities, etc.

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