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Route identification of freight vehicles' tour using GPS probe data and its application to evaluation of on and off ramp usage of expressways

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Abstract

GPS-based probe car data is useful for studying traffic situations that roadside sensors cannot detect. However, the ambiguity in the map-matching and route identification processing of link-based probe data analysis has been a difficult problem especially in urban areas with many high-density roads and elevated roads. Unlike situations in which navigation systems are to be developed, in offline analysis, there are cases where a real-time constraint is not imposed. This means we can refer to data from any time of day of a vehicle tour and use much more computer resources than would be available for real-time embedded systems. In this paper, a new method of map-matching and the route identification based on dynamic programming is proposed and its effectiveness is shown in comprehensive field data tests.

Keywords: Probe cars; freight vehicle; map-matching; logistics; GPS

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1. Introduction

The authors' major concern is the evaluation of road network usage by freight-carrying vehicles. It is important to know which kinds of roads, e.g., an expressway or ordinary road, freight vehicles use. This paper describes an algorithm of map-matching and route identification that uses GPS probe data to

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identify freight vehicles' usage of expressway off- and on-ramps. This is useful information because no previous study has made it clear when freight vehicles use expressways or when they get on or off expressways. By studying these characteristics, one can evaluate the current expressway network from the viewpoint of freight traffic and such evaluations may point to the need to modify the network structure.

2. Literature review

There have been several studies that may be related to the topic of this paper. One direction of research has aimed at estimating the travel time based on probe data. Early work on probe-car-based measurements of travel time appeared in the late 1990s. For instance, Yokota (1999) described the principles underlying a method of estimating the travel time based on the up-link travel time sent from vehicles via the communication capabilities of roadside infra-red vehicle detectors. That paper's author also described methods of estimating and predicting travel times from an otherwise insufficient number of probe data (Yokota, T., 2007). Using probe data for the analysis of traffic phenomena has been reported, and most of this effort has been devoted to evaluating route selection models or estimating passenger-vehicle traffic (Miwa, T. *et al.* (2003), (2004), Tsuge, M. *et al.*, (2010)). In contrast, there have been a limited number of probe-data-based freight vehicle surveys (Figliozzi, M. (2007), and Greaves, S.P. (2008)).

Another direction in probe car research concerns the identification of driver behaviour in choosing routes. Kitamura (2003) and Miwa (2003), (2004) used taxi-probe data to analyze driver behaviour related to choosing routes. Data cleansing is an important issue when processing probe-car data. Sarvi (2002)) proposed a method of data cleansing and identifying the end of a trip; however, the proposed technology was for buses and taxis and was not intended to be applied to freight-carrying vehicles. This means freight vehicles have barely been studied in the current literature.

Several studies have been done, however, on the trip chains or tours of commercial vehicles. Figliozzi (2007) proposed a set of continuous approximation models for four different types of tours. He discussed the likely impact of policies or networks changes by using the models. Figliozzi (2010) also formulated a tour model and analyzed the impact of congestion with respect to different conditions. He categorized tours into three classes based on the average distance per stop and the percentage of time spent driving with an example of empirical tour data in Sydney. Greaves (2008) made a probe-data-based analysis of commercial-vehicle-tour data and described a pilot survey in Melbourne. He also discussed potential applications such as estimating O-D,(Origin-Destination) matrices and constructing trip-length distributions. However, the pilot survey studied only a few vehicles (30 trucks) and was not intended to obtain unbiased results. Holguin-Veras (2005) discussed the trip chain behaviour of commercial vehicles and estimated the probability of the trip's purpose with respect to the vehicle category and the number of trip chains, average number of stops, and length of trip chains from data in travel diaries of truck drivers in Denver, USA. Browne *et al.* (2009) reviewed urban-freight survey techniques in the UK since the 1970s to the present mostly on the basis of questionnaires and not based on probe data. Christian (2009) reviewed urban-freight surveys in France with case studies carried out in Marseilles, Bordeaux, and Dijon. The surveys were mostly based on questionnaires administered to drivers. Anderson (2000) presented survey results of questionnaires conducted in Norwich and London, Great Britain. Vleugel and Janic (2004) statistically investigated the route-choice behaviour of freight drivers on the basis of interviews and questionnaires done in Dutch cities. To the best of the authors' knowledge, none of the existing research has described a practical method of extracting tour data from GPS probe data. Fig. 1 shows an example of a probe survey recently conducted by the authors (Yokota, T. and Tamagawa, D., 2010). This study involved cell-based analysis instead of a link-based analysis, because of the absence of feasible map-matching and route identification algorithms (Yokota, T. and Tamagawa, D., 2011). In the probe density map in Fig. 1, the solid blue lines correspond to the high-probe-density cells and the gray lines correspond to the low-probe-density cells. The cell size is 20 by 20 meters, which is roughly comparable to the resolution of GPS data. The threshold that separates the high- and low-probe-density cells is 30 probes/cell·month, which roughly means that at least one of the 300 trucks visits these links every day on average.

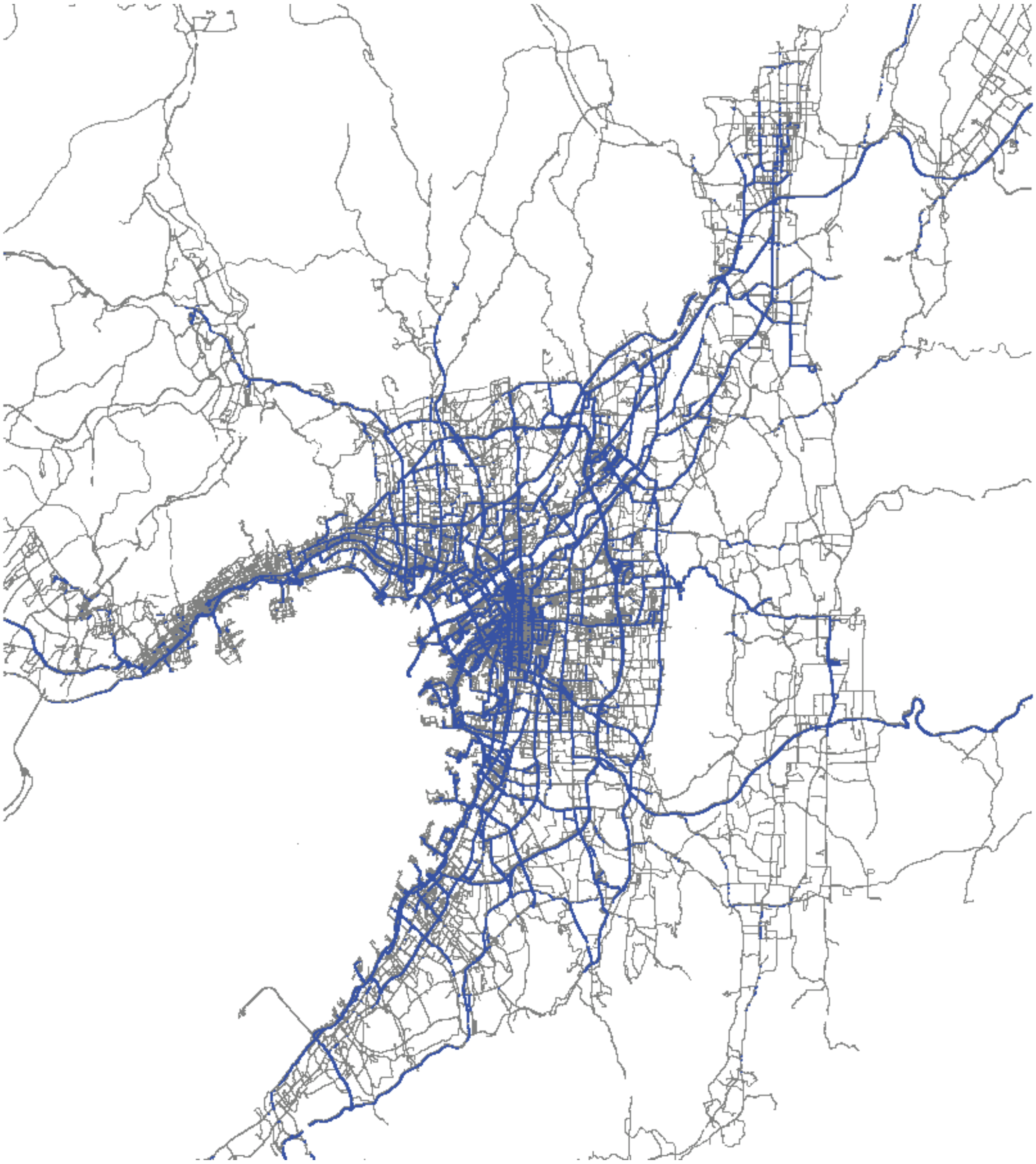

Fig. 1. Probe survey of freight traffic conducted in October, 2009 (Yokota, T. and Tamagawa, D., 2010, 2011)

While map-matching has been extensively developed for navigation systems since the early 1990s, the technology of real-time map-matching is not suitable for the authors' research area of offline probe surveys. One of the authors' goals is the evaluation of the ease of access and egress at expressway on- and off-ramps from the viewpoint of freight traffic flow. Regarding traffic in an urban city such as Osaka, an algorithm needs to be able to make an accurate distinction between elevated expressways and ordinary roads, because ordinary roads often run just underneath the expressway or very close to and parallel to the expressway. To overcome this obstacle, we introduced a global measure to the map-matching and route identification algorithm which takes into account the road network connectivity or vehicle reachability through the past, present, and future. This acts as a contextual aid for the probe data obtained from GPS receivers. The authors developed a dynamic programming based map-matching and route identification algorithm that is computationally feasible and generic. The idea is illustrated in Fig. 2. The triangles show the positions and their headings obtained from the GPS data. In real-time cases, it will have a delay in obtaining a correct matching answer if the two roads run closely spaced and parallel. In this case, the matching result easily gives a wrong-way answer for several hundred meters. In contrast, if the system has access to the future probe data, it can easily find the correct answer. Even though the algorithm is not meant to be used in real-time applications, it is still applicable to some real-time systems such as traffic information systems where delays of several minutes may be acceptable.

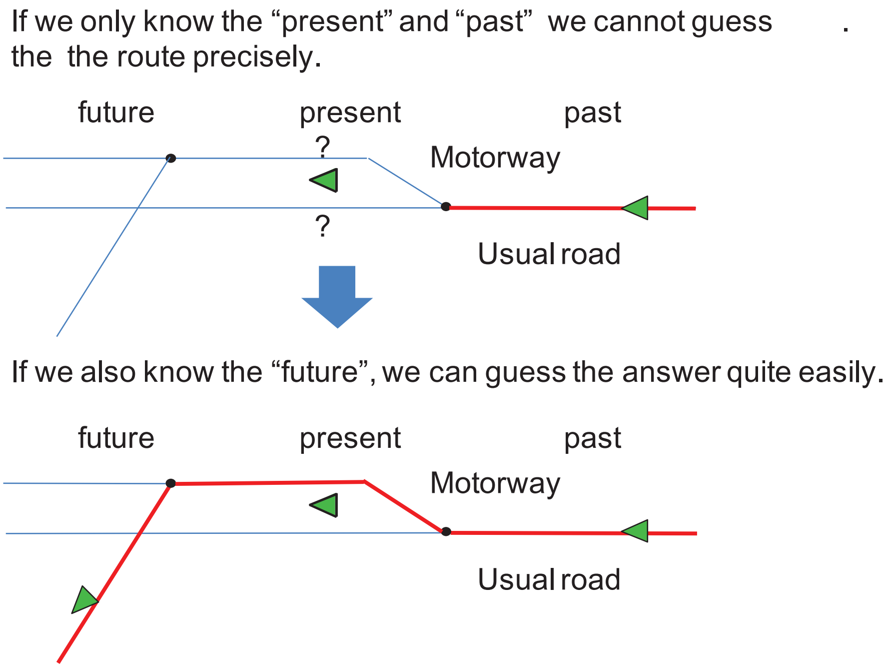

Fig. 2. Concept of a new method of map-matching

3. Formulation of the algorithm

3.1. Local measure

Let us assume that we have access to GPS probe time series data of whole vehicle tours for every day. Furthermore, let us assume that the time interval of the probe is short enough so that every road link the vehicle passes over must have at least one probe data to be matched or projected. We can define a function that evaluates the local goodness of match (Eq. (1)). This is an additive version of the local evaluation function, and it consists of three terms. The term $\mathrm{f}\left(\mathbf{p}_{\mathrm{p}}(\mathrm{t}_{\mathrm{i}}), \mathrm{l}_{\mathrm{j}}\right)$ evaluates the distance between the GPS probe point $\mathbf{p}_{\mathrm{p}}(\mathrm{t}_{\mathrm{i}})$ and a candidate link l_{j}. The links can be directed or non-directed. There are usually a number of candidate links that need to be taken into account.

$$E(i,j) = f\left(\boldsymbol{p}_p(t_i), \boldsymbol{p}_{m,j}(t_i)\right) + g\left(\theta_{p,i}, \theta_{l,m}\right), \tag{1}$$

$$f\left(\boldsymbol{p}_p(t_i), \boldsymbol{p}_{m,j}(t_i)\right) = e^{-\frac{\left\|\boldsymbol{p}_p(t_i) - \boldsymbol{p}_{m,j}(t_i)\right\|^2}{2\sigma^2}}, \tag{2}$$

$$\boldsymbol{p}_p(t_i) = \left(x_p(t_i), y_p(t_i)\right), \tag{3}$$

$$\boldsymbol{p}_{m,j}(t_i) = \left(x_m(t_i), y_m(t_i)\right). \tag{4}$$

The distance is given by the length of the line of the perpendicular projection to the candidate link from the probe point. Usually, a link is composed of several sections which are connected by interpolation points in order to approximate the geometrical shape of each link. The projection is done onto a section which has two interpolation points on its ends. The second term $\mathrm{g}\left(\theta_{\mathrm{p,i}}, \theta_{\mathrm{l,m}}\right)$ in Eq. (1) evaluates the difference between the direction of the vehicle heading $\theta_{\mathrm{p,i}}$ and the link direction $\theta_{\mathrm{l,m}}$. Notice that indices p, l and m stand for "probe", "link" and "map", respectively. σ is the standard deviation of the position error of GPS which is set to 20 m. The link direction is usually calculated from the positions of two adjacent interpolation points which is indexed by *l*, and the regulation information (a link attribute). $\mathbf{p}_{\mathrm{p}}(\mathrm{t}_{\mathrm{i}})$ and $\mathbf{p}_{\mathrm{m}}(\mathrm{t}_{\mathrm{i}})$ are the position vectors of probe data at time t_{i} and that of the projection point.

3.2. Global measure and dynamic programming

We introduce a global measure F to be maximized which is given by Equation (5). This evaluates the overall goodness of match throughout a tour that the freight vehicle goes through in a day.

$$F(s(i)) = \sum_{i=0}^{P-1} \sum_{j \in \varphi_i} \sum_{j' \in \varphi_{i-1}} E(i,j) \cdot a_{j,j'} \cdot \delta\{j', s(i)\}, \tag{5}$$

where

$$a_{j,j'} = 1, when\ candidate\ link_j of\ stage\ i\ is\ reachable\ from\ candidate\ link_{j'} at\ stage\ i-1 \tag{6}$$

$$a_{j,j'} = 0, when\ candidate\ \ link_j\ of\ stage\ i\ is\ not\ reachable\ from\ \ candidate\ link_{j'}\ at\ stage\ i-1.$$

By “stage”, the authors mean the index of the time sequence of probe data. $\varphi_i$is a set of candidate links at stage i. Candidate links are neighboring links from the position of the probe data at stage i. For simplicity, we assume that every link in the target area is assigned a unique index number, although the digital road maps used in most GISs are mesh-based and node numbers or index numbers are local to each mesh and not unique over meshes. The index i which appears in Eqs. (5) and (6) indicates the time sequence of the probe data. The indices j’ and j in Eqs.(5) and (6) indicate candidate links in succeeding stages i-1 and i. . $\delta\{\quad\}$ Is Kronecker’s delta function, which gives 1 when the arguments coincide and gives 0 otherwise. Maximizing the measure of Eq. (5) is identical to solving a discrete decision problem which determines the series of optimum choice of link indices s(i), i=0,..,P-1, where P is the total number of probe data of the vehicle on the day. We can solve this problem in a simple and efficient manner through the dynamic programming paradigm after deriving recursive equations Eqs. (7) and (8) from Eqs. (5) and (6).

$$w(i,j) = max_{j'}\{w(i-1,j')\cdot a_{j',j} + E(i,j)\}, \qquad (7)$$

$$j = 0,1,2,\ldots,Q-1,$$

$$j' = 0,1,2,\ldots,Q-1,$$

$$i = 0,1,2,\ldots,P-1,$$

$$F\big(s(i)\big) = max_j\, w(P-1,j), i = 0,1,2,\ldots,P-1\,. \qquad (8)$$

4. Evaluation of the proposed algorithm

The proposed algorithm was evaluated by feeding it with GPS probe data from the 2009 experiment. The authors’ major concern was the evaluation of the usefulness of ramps of expressways. Hence, we evaluated the algorithm from the following viewpoints.

4.1. Effects of dynamic programming for closely parallel road cases

There are many cases where the past and the present probe data are not sufficient to decide on the correct roads. The effectiveness of the proposed algorithm is shown in this section by examining typical examples. Fig. 3 shows the results of local matching of an on-ramp of the Hanshin Expressway Higashi-Osaka line. Ramp links are shown in brown. Coloured triangles show the positions and headings of the raw GPS data. Black points on road links indicate the map-matched points on the digital road map. Red circles indicate that the algorithm matched incorrect roads. The matching algorithm based only on the local measure failed to detect the on-ramp manoeuvres of the freight vehicles. Fig. 4 shows the results of the dynamic programming without future probe data, that is, what we call forward chaining optimization. It also failed to detect the on-ramp manoeuvres for the most part. Fig. 5 shows the results of the proposed algorithm based on dynamic programming using future probe information in addition to present and past information. All of the on-ramp manoeuvres were detected in spite of considerable fluctuations in the position data of the GPS receiver that may have been caused by high-rise buildings. Fig. 6 shows the satellite image of this expressway. There are four closely parallel roads in each direction, and it is a very difficult place for the conventional algorithms to detect the on-ramp manoeuvres.

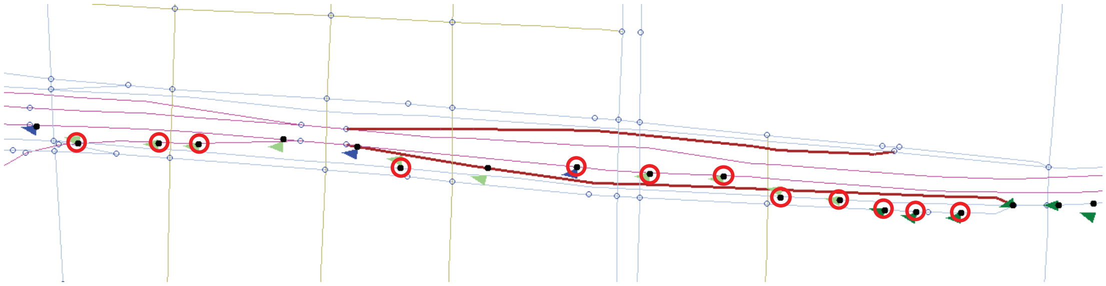

Fig. 3. Matching results using local measure (Vehicle with anonymous ID#159 on Oct. 1, 2009) (Coloured triangles show the positions and headings of raw GPS data. Black points indicate the map-matched point on digital road map. Red circles indicate that the algorithm matched incorrect roads.)

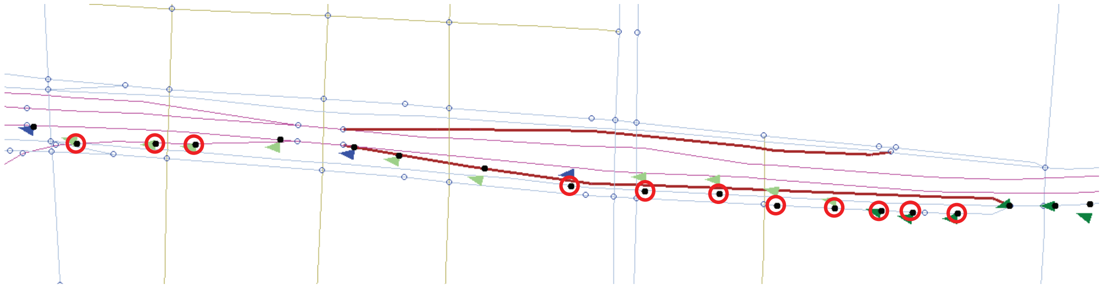

Fig. 4. Matching results gotten by forward chaining algorithm (Red circles indicate that the algorithm matched incorrect roads.)

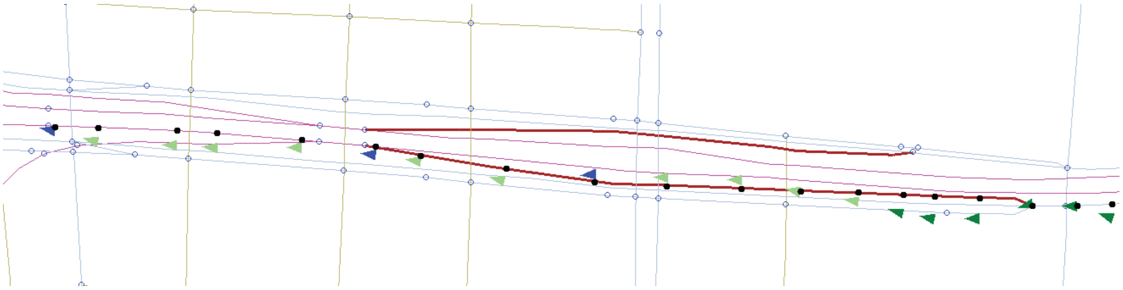

Fig. 5. Matching results using global measure with future probes

Fig. 6. Satellite picture of the Hanshin Expressway Higashi-Osaka line test place

4.2. Overall evaluation of detecting on– and off–ramp manoeuvres

The authors selected 100 test data (50 on-ramps and 50 off-ramps) from the October, 2009 probe experiment (Yokota, T. *et al.*, 2010). We counted the number of ramps where freight vehicles manoeuvres were correctly detected and the number of ramps where they were incorrectly detected. The success rates of the proposed algorithm and other methods were compared. The proposed algorithm correctly detected all of the on- and off-ramp manoeuvres, whereas the forward chaining algorithm detected only 75% of them and the local measure algorithm 49%. Even though the proposed algorithm may give incorrect results depending on the GPS reception conditions, shapes of the road links, errors in digitizing road maps, and so on, these results prove its usefulness.

Note that here the local measure algorithm just finds a series of solutions by maximizing Eq. (1). The forward chaining algorithm is not a local measure algorithm, and it does not use “future” probe data. This situation is identical to real-time cases. Hence, the results of the forward chaining algorithm show the limitation of real-time algorithms.

4.3. ON- and OFF-ramp detection

The authors tried to analyze the usage of on-ramps by freight vehicles. Fig. 7 shows an example of the profile of the road classes which a freight vehicle chose on one day (October 1, 2009). Since the tour is matched to optimum links by the matching algorithm, the road class can be obtained by referring to the digital road-map data base. Road class 2 corresponds to the Hanshin Expressway. This graph clearly shows that the vehicle used the Hanshin Expressway twice on this day. Fig. 8 shows the profile of the score of each stage in the dynamic programming. It is given step-wisely by Eq. (7) starting backward from the total maximum value given by Eq. (8). It monotonously increased with the time of day and had a number of reset points where the algorithm could not find any optimum neighbor links to be matched maybe because the vehicle entered parking spaces. Fig. 9 shows the frequency of on-ramp usage detected by the route identification algorithm for 300 vehicles during October 1 to 7, 2009. Fig. 10 shows the locations of the top 30 on-ramps. Off-ramp usage could be also detected in the same manner. The results are well spread. An analysis of ease of access and egress is currently underway.

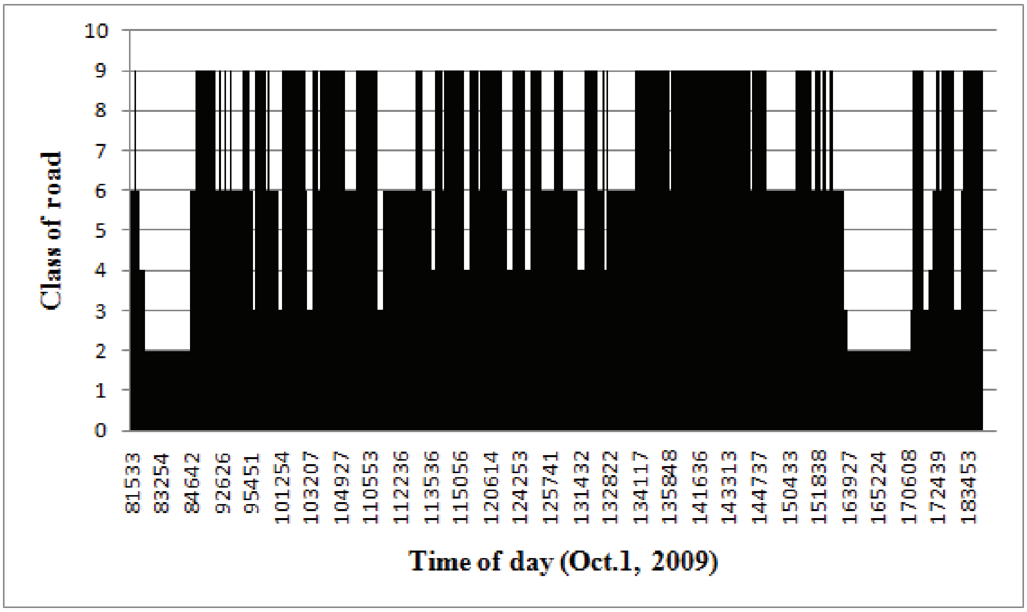

Fig. 7. Road class profile of one day tour of vehicle with anonymous ID#159 (Class 2 corresponds to the Hanshin expressway and Class 1 corresponds to NEXCO highways)

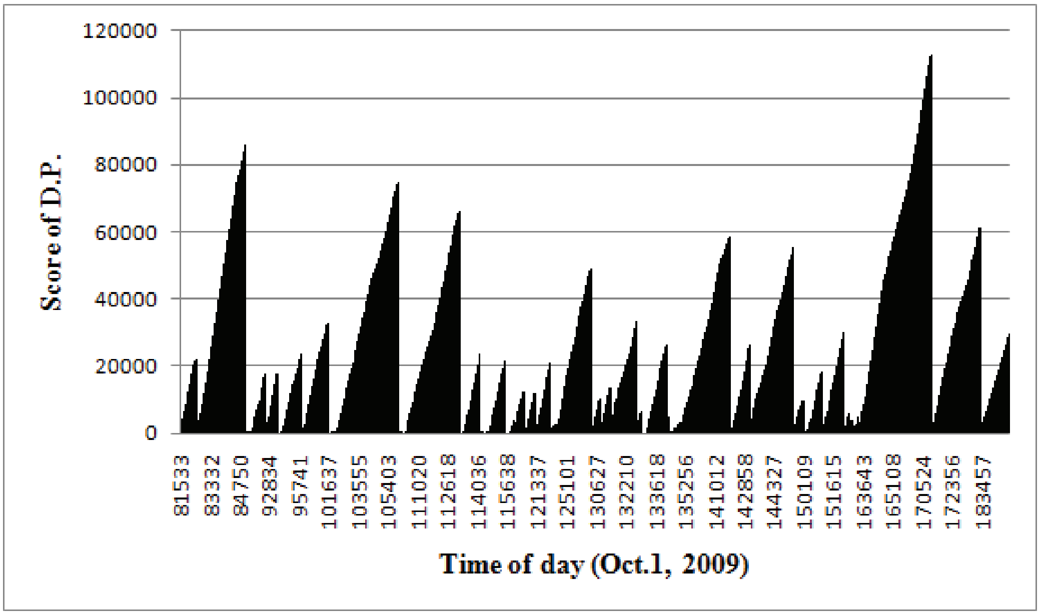

Fig. 8. Profile of D.P. score of vehicle with anonymous ID#159

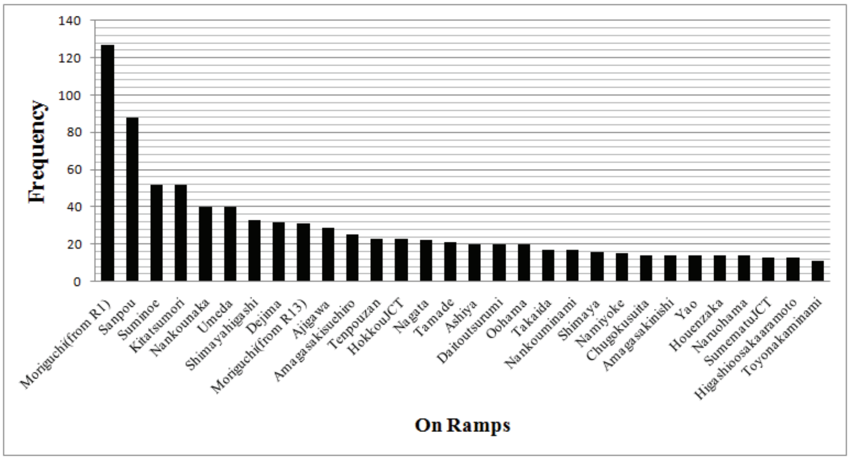

Fig. 9. Usage frequency of on ramps

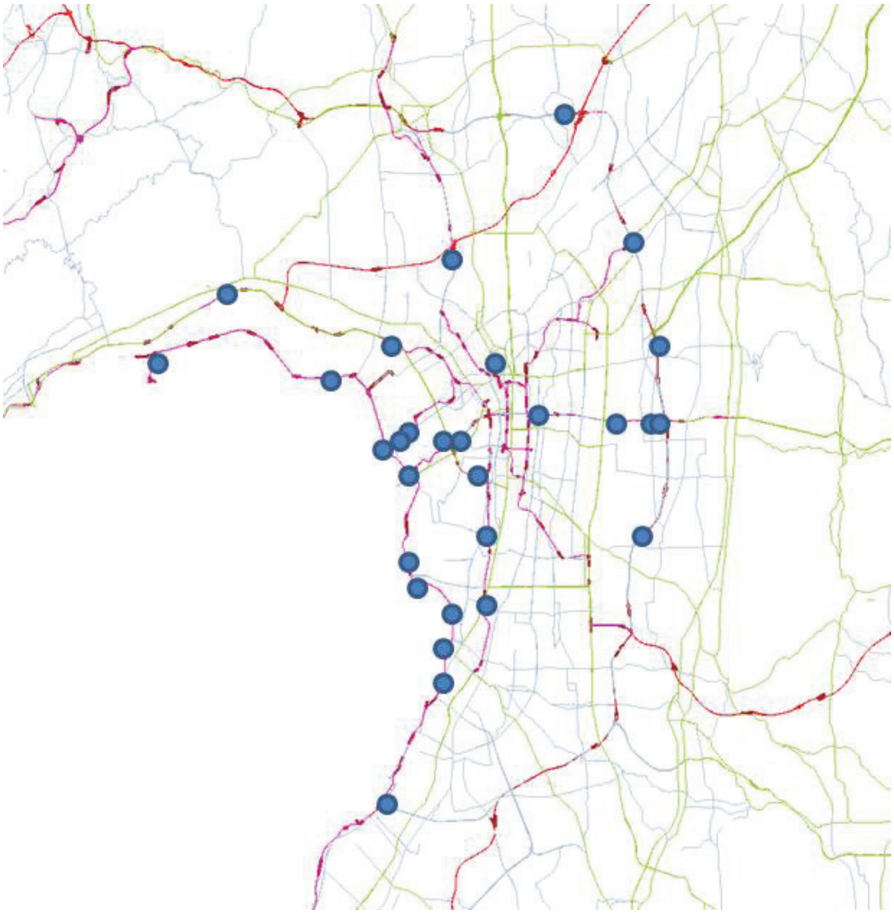

Fig. 10. Top 30 on ramps of 300 freight vehicles (Blue circles show the top 30 on ramps)

5. Conclusion

A new map-matching and route identification algorithm for probe data was developed. Algorithm based on dynamic programming takes the whole tour data into account, and in an experiment, it successfully detected almost all of on- and off-ramp manoeuvres of freight-carrying vehicles in comprehensive evaluation using actual GPS probe data from freight vehicles. On the basis of this technology, we can analyze freight-vehicle tours in detail in order to improve logistics and determine a strategy to improve expressway service levels by using actual GPS probe data from freight vehicles. For example, on-ramp usage frequency was determined from data on 300 freight vehicles, and it showed a moderately spread spatial pattern. Off-ramp usage could also be detected. A detailed analysis of the ease of access and egress is currently underway.

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