Real-Time Origin-Destination (OD) Estimation via Anonymous Vehicle Tracking

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Abstract—**With the advent of Advanced Transportation Management and Information Systems (ATMIS), much attention has been paid to the estimation of dynamic or time-variant OD matrices, as development of improved methods for the derivation of OD-based real time traffic information is vital for analysis of transportation systems and various ATMIS strategies involving traveler information systems and route guidance, dynamic traffic assignment, and adaptive traffic signal control, among others. This study performs a systematic simulation investigation of the performance and feasibility of anonymous vehicle tracking in signalized networks using the Paramics simulation model. Previous research experience with vehicle reidentification techniques on single roadway segments is used to investigate the performance obtainable from tracking individual vehicles across multiple detector stations through a network to obtain real-time OD path flow information such as travel time and volume. The findings of this and subsequent studies serve as a logical and necessary precursor to possible field implementation in signalized networks of vehicle reidentification techniques.**

Index Terms—**vehicle tracking, vehicle reidentification, OD-based real time traffic information**

I. Introduction

A NEW GENERATION of Advanced Transportation Management and Information Systems (ATMIS) is now widely under development, for applications in traveler information, route guidance, traffic control, congestion monitoring, incident detection, and system evaluation, across extremely complex transportation networks. However, the limitations, and often large errors, inherent in present vehicle surveillance systems greatly diminishes the ability of public agencies to effectively control and manage highways and transit systems, and to provide useful, timely and accurate travel information. New types of travel data, in real-time, are essential for effective implementation of ATMIS. In the past, such data were extremely difficult to obtain. To address this need, there has recently been substantial interest in the United States and Europe, and particularly in California, in implementing vehicle reidentification systems, initially using the extensive existing inductive loop infrastructure, and ultimately using emerging technologies such as video and laser detectors, the Global Positioning System (GPS) of satellites, and on-board vehicle sensors and wireless communications.

In the future, data fusion techniques will likely be developed to combine the output features of multiple types of sensors. However, regardless of the technologies used, real-time travel time and origin-destination (OD) information have been identified as particularly important outputs of such systems. In addition, relatively inexpensive, anonymous tracking systems, without potential privacy concerns (as exist with tagged automatic vehicle identification systems) are preferred.

A general vehicle reidentification system using inductive loop signatures to uniquely but anonymously track individual vehicles, has been formulated and tested in recent years at the University of California, Irvine. By using non-obtrusive and anonymous tracking methods, individual vehicles can be identified and correlated over numerous identification stations, and very specific real-time data can be obtained for each tracked vehicle. The results have been reported by Ritchie and Sun [1], Sun et al [2]-[3], Sun and Ritchie [4], Oh and Ritchie [5] and Oh et al [6].

This approach has yielded very accurate real-time section travel time, speed, delay, level of service, density, vehicle classification and origin destination information from either double or single loop detector stations. The algorithms have also been implemented in the field at a major intersection in Irvine and real-time performance information provided to operators at the city's traffic management center. Previously, an off-line freeway implementation was investigated, and yielded excellent results. For example, average real-time section or link travel times, and intersection delays, have been estimated with errors of 3-12%, with aggregation periods of up to 15 minutes. No studies have been undertaken of the accuracy of OD information, except for turning movements at an individual intersection. Although the potential for extension of this approach to network applications is very high, further feasibility study is necessary before investing in network-wide

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implementation. The main purpose of this study is to demonstrate the potential feasibility of a new proposed framework for anonymous vehicle tracking using the Paramics (PARAllel MICroscopic Simulation) microscopic traffic simulation model.

The insights obtained by the authors in previous research with single roadway segments have been used as input to investigate the performance obtainable from tracking individual vehicles across multiple detector stations through a network to obtain real-time OD path flow information such as travel time and volume. The findings of this study serve as a logical and necessary precursor to possible field implementation in signalized networks of vehicle reidentification techniques for transportation systems analysis.

The first section of this paper addresses an overview of vehicle tracking and time-variant OD estimation. The framework for the proposed anonymous vehicle tracking system is presented in the second section. The simulation experiment using Paramics is conducted and the results are discussed in the third section. Finally, the conclusions and future research are presented.

II. Overview

A. Vehicle Tracking

The literature on vehicle tracking can be grouped into several categories based on the technologies used, such as GPS, vehicle tag-based AVI, and video image processing (VIP). GPS is a potentially valuable tool for traffic surveillance due to its capability of providing positioning data for individual vehicles [7]-[10]. The major limitations of GPS though are currently minimal fleet penetration, varying accuracies, and signal loss in urban areas due to tall buildings, tunnels, and trees etc. The most widely-used AVI technologies are based on license plate identification and the use of transponder tags [11]-[12]. A number of studies have utilized VIP methods for localized vehicle tracking in a lab environment [13]-[17]. However, video sensors are not yet widely deployed and often involve relatively high initial costs with reliabilities that are yet to be proven. In addition, public perceptions of significant privacy concerns remain for many GPS, AVI and VIP systems.

Consequently, a non-intrusive and anonymous vehicle tracking surveillance technology that could utilize the vehicle features involving vehicle length, height, width, and color etc, would be highly advantageous for assessing real-time performance of transportation systems.

B. Time-variant OD estimation

Previous studies to estimate time-variant OD matrices can be categorized by two factors: the network configuration and use of a traffic assignment model. Regarding network configuration, the approaches can be separated into two further categories. The first group applies to simple networks, which means individual intersections or freeway segments with no route choice [18]-[26]. The second applies to more general networks and is the most challenging problem [27]-[33]. Generally most approaches to obtain time-variant OD matrices in signalized networks have used link volumes with an assumption that path choices are known. However, in the proposed vehicle tracking approach, actual OD paths and their characteristics are obtained directly as an output of the system.

III. The Proposed Anonymous Vehicle Tracking System

Recently, sensor technologies have advanced to the degree where individual vehicle features are obtainable [1]-[6]. Examples include use of existing loop detectors with high speed scanning detector cards to generate inductive signatures, laser-based detection systems [34] providing vehicle length, and video-based vehicle signature generation [35] using VIP technology. The vehicle features contain a valuable set of information that enables us to identify the characteristics of individual vehicles such as length, width, height, and color. Moreover, vehicle lane information, vehicle speed, signal phase information, and vehicle arrival time can also be obtained and considered as vehicle features.

In on-going research by the authors, a real-time traffic surveillance system based on vehicle reidentification technology that utilizes vehicle inductive signatures is operating at the intersection of Alton Parkway and Irvine Center Drive in the City of Irvine, California. The present system yields valuable real-time traffic information obtained by matching vehicle signatures from upstream and downstream detector stations. Real-time performance information from the intersection has been provided to operators at the city's traffic management center. The present intersection vehicle reidentification system has yielded real-time intersection travel time, speed, delay, level of service, vehicle classification and localized origin destination information, from either double or single loop detector stations (many other performance measures can also be derived). Although individual vehicle matching rates of about 30-50% have been obtained to date, a new vehicle reidentification algorithm has been developed and tested, which is expected to significantly enhance the vehicle matching performance.

Vehicle tracking broadly belongs to the field of object identification, which is the task of determining whether two observed objects are the same. In the transportation context, the object of consideration is a vehicle. The vehicle tracking problem on transportation networks defined by vehicle features is to identify and correlate individual vehicles' features throughout the temporal-spatial search space. In other words, features of individual vehicles are successively traced over numerous detection stations.

The basic concept of vehicle tracking proposed in this study consists of sequential search space reductions. Firstly, origin and destination stations are pre-determined in order to define the search space. When individual vehicles (VEH_i) pass the downstream detection stations, the vehicle features including detection time (f_{dt}) and location (f_{dd}) are recorded. Then the algorithm establishes the candidate set of upstream vehicle features ($VEH_j = [f_{ud}, f_{ut}, F_{us}]$) that potentially would be matched. Then the most similar feature vector among the candidates is identified, a match is declared ($F_{us} = F_{ds}$) and vehicle path history ($PATH_i^{new}$) is updated. After conducting the matching procedure for vehicle features, the algorithm investigates if an identified upstream detection station is the given destination station. Once the upstream station is identified as the destination, vehicle information is acquired by recording the vehicle history. To produce real-time OD-based traffic information, individual vehicles information is aggregated based on a given aggregation interval. The proposed framework for vehicle tracking is presented in Figure 1. Further details about vehicle identification that correspond to the procedure of "turning filtering – candidate set optimization – vehicle identification" in Figure 1 are discussed by Ritchie et al [36].

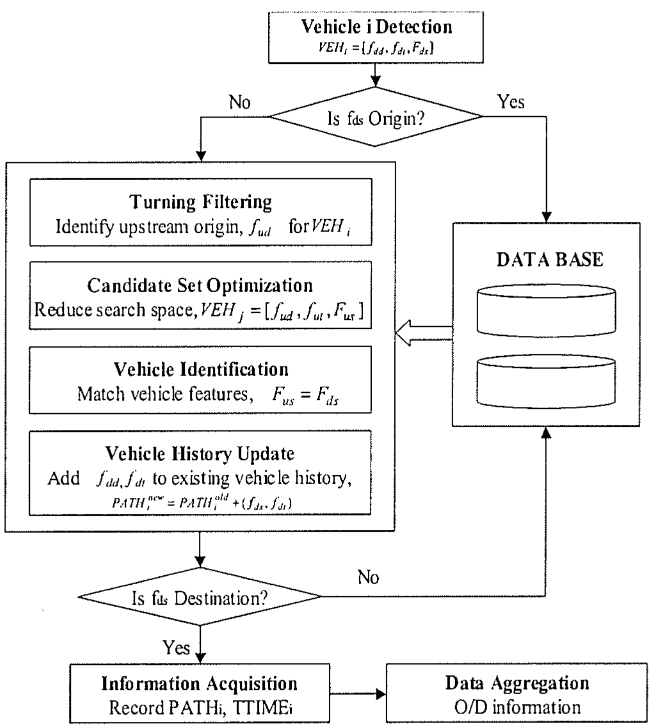

Fig. 1. The proposed vehicle tracking framework

IV. Simulation Experiment

A. Proposed Simulation Approach

To demonstrate the potential feasibility of the proposed vehicle tracking system in terms of deriving real-time OD-based traffic information, a microscopic traffic simulation model was used.

Paramics (PARAllel MICroscopic Simulation) was used to gather the sample data. Paramics is a suite of high-performance software tools for microscopic traffic simulation. The movement and behavior of individual vehicles are modeled in detail for the duration of their entire trip. One of the nice features of Paramics is that it can be customized. Access is available through a functional interface or application programming interface (API). APIs allow additional functionality by adding more external modeling routines. This is an essential feature of Paramics that allowed the implementation of the various ATMIS application algorithms. The test network modeled by Paramics has eight origin/destination nodes and four signalized intersections operated by actuated signal control as shown in Figure 2.

Two data sets using Paramics were generated, representing congested and uncongested traffic conditions. Congested traffic conditions result in individual cycle failures on the simulation network. Using the Highway Capacity Manual [37] Level Of Service (LOS) criteria, congested and uncongested traffic conditions can therefore be categorized into LOS 'A – C' and 'D-F' respectively.

Each data set includes not only detection time and location but also characteristics for individual vehicles, such as vehicle length, width, height and color. Effects of vehicle tracking performance on accuracy of real-time OD-based traffic information were investigated using a Monte Carlo simulation method. In simulating the vehicle tracking system on this signalized network, exogenously determined correct matching and mismatching rates were applied. Then, all matched vehicles' information such as path flow and path travel time were computed with a given aggregation time interval.

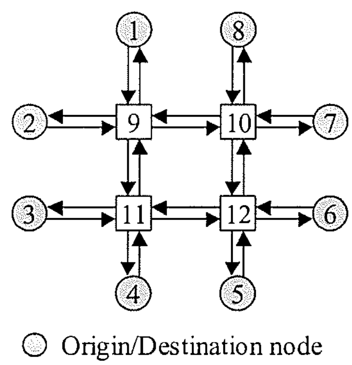

Fig. 2. Test network

B. Results

As a performance measure, a Mean Absolute Percentage Error (MAPE) was calculated by comparing with the case of 100% correct vehicle tracking. This simulation procedure was repeated for 100 runs and the MAPEs were averaged to obtain an overall performance measure. Two-hour simulations for congested and uncongested traffic conditions, respectively, were performed.

$$MAPE = \frac{\sum_{n=1}^{N}\sum_{r=1}^{R}\left[\left|\frac{PATH_{obs,nr} - PATH_{est,nr}}{PATH_{obs,nr}}\right| \times 100\right]}{N \cdot R}$$

where,

$PATH_{obs,nr}$: Observed path flow/travel time on path r at time step n (correct vehicle tracking)

$PATH_{est,nr}$: Estimated path flow/travel time on path r at time step n (reidentified vehicle tracking)

N : Total number of time step

$$= \begin{cases} 24: & 5 \text{ min. aggregation} \\ 12: & 10 \text{ min. aggregation} \\ 8: & 15 \text{ min. aggregation} \end{cases}$$

R : Total number of paths (72 paths in 56 OD pairs)

Tables 1 and 2 show the MAPE of the path flow and path travel time based on the proposed vehicle tracking system. Tracking performance represents the ratio of correctly tracked vehicles in a given time interval. The performance evaluations presented in Tables 1 and 2 were obtained by comparing "true" path flow and travel time from 100% correct vehicle tracking and "estimated" path flow and travel time from vehicle tracking based on vehicle reidentification and considering various tracking performance levels. The major findings from the simulation experiment are summarized as follows:

(1) The path flow estimates show the potential feasibility of the proposed vehicle tracking algorithm. In the congested traffic conditions, we found that MAPEs less than 10% are achieved with a 0.6 tracking performance for the 15 min. aggregation intervals, and even with a 0.3 tracking performance the MAPE of path flow was less than 30%.

(2) The accuracy of travel time estimation shows highly promising results, which encourages the application of the proposed system in the real world. Less than 10% MAPE was achieved with 0.6 tracking performance for the 15 min. aggregation in the congested traffic conditions, and less than 30% MAPE with 0.3 tracking performance.

(3) The aggregation interval is an important issue for designing a real-time traffic information system. As shown in the evaluation results, the relationship between reliability levels resulting from vehicle tracking based on vehicle reidentification and different aggregation intervals should be analyzed further in order to identify an appropriate aggregation interval for a certain level of reliability.

V. Conclusion

This study has presented a framework for studying the feasibility of an anonymous vehicle tracking system for signalized networks. The potential feasibility of such an approach was demonstrated by simulation experiments for a small test network. A Monte Carlo simulation method utilizing the sample data obtained from the Paramics microscopic traffic simulation model was used in order to investigate the effects of vehicle tracking performance on real-time OD-based traffic information estimation. The findings of this study can serve as a logical and necessary precursor to possible field implementation in an actual signalized network of the proposed system. It is believed that the proposed methodology in this study can offer a valuable tool to operating agencies interested in real-time congestion monitoring, traveler information, control, and system evaluation. In the future ongoing research by the authors will apply similar techniques to a major traveler corridor in Southern California.

Table 1 Overall performance for the MAPE under unconGested traffic conditions

MAPE(%)	Aggregation Interval					
	5 min.		10 min.		15 min.	
Tracking Performance	Path Flow	Path travel time	Path flow	Path Travel Time	Path Flow	Path travel time
0.1	146.58	23.66	106.87	24.91	87.97	21.88
0.2	97.76	21.47	72.73	20.54	58.69	16.47
0.3	65.07	18.90	50.15	16.77	40.37	12.67
0.4	47.68	16.33	38.57	13.74	30.88	9.98
0.5	44.8	13.37	33.65	11.01	26.58	7.69
0.6	25.63	11.02	20.10	8.95	16.58	5.83
0.7	16.12	8.75	13.28	7.08	10.99	4.26
0.8	10.34	6.39	8.76	5.19	7.40	2.77
0.9	3.81	3.89	3.32	3.13	3.14	1.04

Table 2 Overall performance for the MAPE under congested traffic conditions

MAPE(%)	Aggregation Interval					
	5 min.		10 min.		15 min.	
Tracking Performance	Path Flow	Path travel time	Path flow	Path Travel time	Path flow	Path travel time
0.1	112.53	31.21	81.13	25.71	68.70	21.43
0.2	74.47	27.19	52.69	22.71	43.93	19.24
0.3	48.80	20.92	34.71	18.93	28.24	15.83
0.4	36.18	18.14	25.56	15.93	20.54	12.77
0.5	24.86	14.82	21.48	12.67	17.08	9.80
0.6	16.65	11.99	11.67	10.07	9.41	7.74
0.7	9.23	9.54	6.57	8.04	4.78	5.88
0.8	5.22	7.00	4.23	5.94	2.45	3.75
0.9	2.11	4.41	1.76	3.79	1.10	1.18

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