Transportmetrica, Vol. 4, No. 3 (2008), 179-194

USING AUTOMATIC VEHICLE IDENIFICATION DATA FOR TRAVEL TIME ESTIMATION IN HONG KONG

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Received 31 January 2007; received in revised form 4 June 2007; accepted 19 June 2007

This paper presents a Real-time Traveler Information System (RTIS) for Hong Kong, in which a novel solution algorithm is proposed for estimation of both the current and instantaneous travel times using automatic vehicle identification (AVI) data. The proposed algorithm also deduces the travel times on the other road links without real-time AVI data. By integration of the filtered real-time and off-line database together, the RTIS can provide area-wide traffic information in the whole network of Hong Kong. The travel time estimates are updated once every five minutes in the RTIS. Observation surveys are conducted during different time periods at a selected path in Hong Kong urban area to validate the RTIS travel time estimates. With the use of the same set of observation data, comparison is also given to the estimation results of the other three existing AVI travel time estimation algorithms: TransGuide, TranStar and Transmit algorithms in US. It was found that the proposed RTIS algorithm could generate the current travel time estimates for the three study periods with the minimum absolute errors and absolute percentage errors. The estimations of instantaneous travel times on the road sections with and without real-time AVI data have also been illustrated. The validation results show that the performance of RTIS is satisfactory and acceptable.

KEYWORDS: Real-time traveler information system, automatic vehicle identification data, current and instantaneous travel time estimates

1. INTRODUCTION

The rapid development of Intelligent Transportation Systems (ITS) and electronic information and communication technologies has alerted researchers to the potential of the application of advanced technologies to alleviate traffic congestion, particularly in large Asian cities like Hong Kong. The Advanced Traveler Information System (ATIS) is one of the options adopted in many Western countries. ATIS detectors are located at some sections of road networks to collect historical and real-time data such as traffic flow and speed data. Link flows and travel times within networks can be estimated based on these partially detected data and delivered to drivers by various means, such as variable message signs, mobile phones and the internet. Drivers are then able to make route choice decisions based on a combination of the received estimated travel times and their own driving experience. It was found that the provision of real-time traffic information significantly affects the route switching behaviour of drivers on expressways (Jou et al., 2004).

There are several techniques for real-time travel time data collection, including electronic distance-measuring instruments, electronic license plate matching, cellular phone tracking, automatic vehicle identification (AVI), automatic vehicle location, and video imaging techniques. Liu and Haines (1996) and Turner (1996) have compared different data collection techniques and summarized their advantages and disadvantages. It was found that, in general, AVI is a proven technology for providing area-wide real-time travel time data. The accuracy of travel time and speed data is high and operating cost is low. The AVI technology is suitable for annual, daily and real-time monitoring

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and for incident detection. Thus, the use of this technology becomes popular in real-time travel time estimation, monitoring and incident detection in recent years (for example, Hellinga and Knapp, 2000; Hellinga, 2001; Dion and Rakha, 2006).

In the US, there are several travel time forecasting systems with the use of AVI data, such as the TransGuide system in San Antonio (Southwest Research Institute, 1998), the TranStar system in Houston (Houston TranStar, 2006) and the Transmit system in the New York/New Jersey metropolitan area (Mouskos et al., 1998). AVI data are collected from roadside tag readers and toll booths for estimating vehicle travel times and speeds and disseminating the information to the traveling public through the internet. However, they are mainly confined to the freeway systems in US.

In Hong Kong, real-time traffic information is available at website portal (http://traffic.td.gov.hk/selection_e.htm) in which images are provided from closed-circuit television (CCTV) cameras located at about 120 strategic roads and road junctions in the urban areas. The CCTV images are updated once every two minutes. From these updated CCTV images, people can know the current traffic conditions on major roads in Hong Kong, in terms of traffic density. However, the limited number of CCTV cameras cannot be sufficient to capture the traffic conditions for the whole territory. Moreover, real-time digital information may be more useful and valuable than video images for most drivers traveling on the roads.

An ATIS prototype, Journey Time Indication System (JTIS), provides current traffic conditions in terms of travel times via displays on three gantry signs near major roads along Hong Kong harbour side since 2003. The estimated journey times are calculated by using speed detection cameras, which capture spot speeds on routes, installed at the approach roads to the three cross-harbour tunnels and in-vehicle global positioning system (GPS) units installed on buses. The JTIS displays are updated at five-minute intervals. However, the coverage of JTIS is limited to the major approach roads to the three cross-harbour tunnels in Hong Kong Island. Therefore, there is a need to collect and make use of additional real-time traffic data for development of the territory-wide real-time traveler information system in Hong Kong. Obviously, there are many challenges and opportunities of developing solution algorithms for transportation planning and travel forecasting (Wu et al., 2006; Boyce and Xiong, 2007) particularly in Hong Kong with limited real-time data available.

In Hong Kong, the JTIS can only provide drivers the current estimated journey times of different cross-harbour routes between Hong Kong Island and Kowloon urban areas. It may not be able to represent the most up-to-minute traffic condition. Figure 1 presents an example for illustrating the difference of current and instantaneous travel times. In the example, the current travel times on the road links AB, BC, CD and DE for time interval of 09:05-09:09 are estimated by vehicles arriving at the exit point E between 09:05 and 09:09 from entry point A. As such, the data collected at exit point E may not represent the traffic condition on links AB, BC and CD at the same time interval. This is because those vehicles arrived at exit point E have already traversed the links before 09:05-09:09. However, the instantaneous travel time estimates are based on vehicles arriving at checkpoints B, C, D and E between 09:05 and 09:09, which are able to represent the most up-to-minute traffic condition on links AB, BC, CD and DE respectively. Therefore, drivers traveling on roads may prefer to the real-time traffic information on the instantaneous travel times rather than the current travel times.

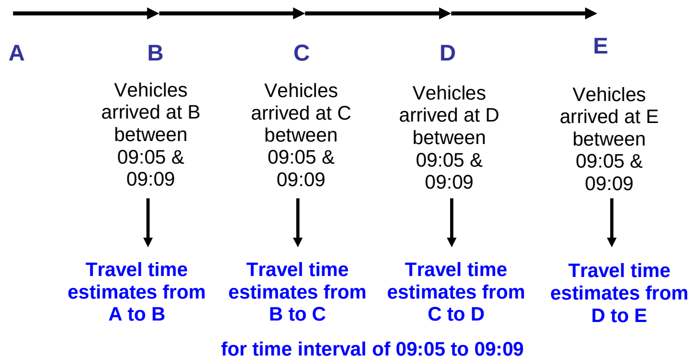

FIGURE 1: Example for illustrating the difference of current and instantaneous travel time estimates

In this paper, a novel solution algorithm is proposed for the Hong Kong RTIS to estimate the travel times using AVI data in Hong Kong. The proposed RTIS algorithm makes two contributions to the existing real-time travel time information system. Firstly, the proposed algorithm can estimate both the current and instantaneous travel times on the road links in the territory-wide road network. Secondly, the proposed algorithm can deduce the travel times on the links without real-time AVI data. It should be pointed out that the proposed algorithm integrates off-line travel time estimates and real-time AVI data together for estimation of current and instantaneous travel times not only on the links with real-time AVI data but also on the links without real-time data. Use of the off-line travel time data is merited in the case of inadequate or short of real-time data at the measurement time interval and is also helpful particularly when the AVI data collection system is broken down.

The RTIS provides area-wide traffic information in the whole network of Hong Kong. The on-line travel times, in RTIS, are estimated and updated based on the real-time traffic data, the off-line travel time estimates and the variance-covariance relationships between road links. Real-time Autotoll tag data, which is a kind of AVI data, is adopted in the RTIS being developed in Hong Kong. The travel time is estimated on the basis of the journey time of those vehicles equipped with electronic tags at tunnel toll-gates. The advantage of making use of AVI data is the large sample size of the data along the paths between tunnels in Hong Kong. The off-line travel time estimates and the corresponding variance-covariance matrices are obtained by a traffic flow simulator (see Section 2 for description). On the basis of these real-time and off-line traffic data, the current traffic conditions on Hong Kong major roads can be updated in a geographic information system (GIS)-based RTIS website portal at five minute intervals. Survey study for a major road network in Hong Kong urban area is presented to validate the RTIS estimates.

The remainder of the paper is structured as follows. Background of the RTIS development is presented in the next section. The RTIS solution algorithm and the other three existing AVI algorithms: TransGuide, TranStar and Transmit algorithms in US are described and compared in the third section. The forth section presents a survey study for validation of the RTIS current travel time estimates and comparison with the three algorithms in US. The estimations of instantaneous travel times on the road sections with and without real-time data are also illustrated. The GIS-based RTIS website portal is shown in the fifth section. Finally, conclusions are given together with recommendations for further study.

2. BACKGROUND OF HONG KONG RTIS DEVELOPMENT

Lam et al. (2002) have developed an off-line traffic forecasting system for short-term travel time forecasting in Hong Kong and empirical validations of the forecasting results have also been given (Lam et al., 2005). In this system, a traffic flow simulator (TFS) has been calibrated for short-term forecasting of travel times by making use of the Hong Kong Annual Traffic Census (ATC) data. The ATC is a collection of traffic-related data of the year at about 110 locations with permanent automatic traffic detectors. A unique feature of the TFS is the use of the variance-covariance information of link travel times and traffic flows in the estimation process. Based on these short-term traffic forecasting results at ATC detector locations (Lam et al., 2006), TFS can be used to estimate the off-line average link travel times and the variance-covariance relationships between road links for the whole territory of Hong Kong.

The off-line short-term travel time forecasting system is useful to travelers for pre-trip planning. However, the real-time traffic conditions have not yet been incorporated in the off-line system and hence travelers are unable to access road condition information whilst on route and on a real-time basis. Moreover, the Hong Kong JTIS only covers a limited number of roads along the harbour side in Hong Kong Island. Therefore, there is a need to provide update and reliable travel time/speed estimates for the whole Hong Kong territory. In view of this, an on-line traffic information system has been proposed specifically for Hong Kong, namely; Real-time Traveler Information System (RTIS).

The RTIS for Hong Kong is jointly developed by the Autotoll Limited and The Hong Kong Polytechnic University. The purposes of the RTIS are to provide update, reliable traffic information as well as to communicate the latest traffic information and advisories to the road users. Travel times/speeds are easily updated in RTIS once every five minutes, by making use of real-time traffic data and results of the off-line travel time forecasting system. The real-time traffic data are Autotoll tag records that are being used for electronic toll collection in Hong Kong, whereas the off-line estimates are the average travel times by link and the link travel time variance-covariance matrices.

In Hong Kong, there are two types of toll-booths in the toll area of road tunnels. The first type of these toll-booths is Autotoll lanes which are mainly for vehicles installed with Autotoll tags, whereas the second type of toll-booths is manual toll lanes for other vehicles without Autotoll tags. There are about 550,000 licensed vehicles in Hong Kong since October 2006. Over 210,000 vehicles have been installed with Autotoll tags to enable toll charge payments at ten road tunnels or links in Hong Kong. Toll-tag penetration is around 40%. The locations of the tolled tunnels/links are shown in Figure 2. Autotoll tag data are collected at the toll-gates of all ten tunnels/links in Hong Kong. The times of vehicles passing through the tunnels/links toll-gates are automatically recorded, processed and transmitted to the central computer system together with the identification information of these vehicles. Based on the Autotoll tag time records, the travel times of vehicles passing between two consecutive tunnels/links are computed at five-minute intervals.

3. RTIS SOLUTION ALGORITHM

3.1 Comparison of AVI travel time algorithms

As AVI tag readers only provide time stamps at which vehicles pass successive

FIGURE 2: Locations of tunnels/links with Autotoll system in Hong Kong (Source: Autotoll Limited)

monitoring stations or checkpoints, it is necessary to filter out the outlier observations because vehicles may make stops or detour along the paths. Since these vehicles would experience a travel time that is atypical, these observations should therefore be removed from the data set of valid observations to avoid producing erroneous travel time estimates. The current state-of-the-art AVI travel time algorithms make use of different sizes of the validity window and the observation intervals for filtering and estimation. For example, the TransGuide algorithm in San Antonio (Southwest Research Institute, 1998) uses a fixed travel time window for data filtering, in which ±20% from the mean travel time associated with observations made in the previous two minutes. The TranStar algorithm in Houston (Houston TranStar, 2006) is similar to the TransGuide algorithm but with a shorter rolling average window of 30 seconds. The threshold of travel time window in Transmit algorithm in New York/New Jersey is defined by users; however, the observation interval is 15 minutes (Mouskos et al., 1998).

Table 1 compares the proposed RTIS solution algorithm against these three existing AVI travel time algorithms. The main difference between the proposed RTIS algorithm and the other AVI algorithms is that the RTIS algorithm integrates both the real-time AVI data and the off-line travel time estimates together so that it can estimate the travel times not only on the links with AVI data but also on the links without real-time data. Moreover, the RTIS algorithm can provide both the current and instantaneous travel time estimates in the road network, whereas the other three algorithms can only estimate the current travel times. The threshold of the travel time window in the RTIS solution algorithm is also dependent on the smoothed average travel time and its standard deviation at current time interval and the number of preceding time intervals without valid observations.

3.2 RTIS solution algorithm

Recently, a data filtering algorithm has been developed by Dion and Rakha (2006) to filter AVI travel time data at low levels of market penetration. Their algorithm utilizes a series of filters to identify valid data within a dynamically varying validity window for the current travel time estimates on the selected path between the entry and exit points. Similar to Dion and Rakha (2006)'s algorithm, the proposed RTIS algorithm is designed and adapted for real-time travel time estimation using AVI data from entry point to exit point on selected paths, particularly for Hong Kong. However, it should be noted that the parameters adopted in the RTIS algorithm have been calibrated using the empirical data collected from observation surveys in Hong Kong.

TABLE 1: Comparison of the AVI travel time algorithms

	RTIS	TransGuide	TranStar	Transmit
Data	• Real-time AVI data • Off-line travel time estimates	• Real-time AVI data	• Real-time AVI data	• Real-time AVI data
Interval of updating window	• 5 minutes	• 2 minutes	• 30 seconds	• 15 minutes
Threshold of travel time window	• Dependent on: (i) smoothed average travel time; (ii) smoothed travel time standard deviation; and (iii) the number of preceding time intervals without valid observations	• Fixed (±20% from the mean travel time)	• Fixed (±20% from the mean travel time)	• User-defined
Application in	• Hong Kong	• San Antonio	• Houston	• New York • New Jersey
Remarks	• Integrate the real-time AVI data and the off-line travel time data together • Both current and instantaneous travel time estimates can be provided on all the road links either with or without AVI data	• Only current travel time estimates are provided on the road links with AVI data • Less accurate under non-recurrent traffic congestion	• Only current travel time estimates are provided on the road links with AVI data • High level of market penetration of AVI-equipped vehicles required	• Only current travel time estimates are provided on the road links with AVI data • Longer time interval for updating

The main difference between the proposed RTIS algorithm with the Dion and Rakha's algorithm is that the proposed RTIS algorithm can provide travel time estimates on all the links either with or without real-time data by using the off-line simulated and real-time updated variance-covariance relationships of the link travel times. Moreover, the RTIS algorithm makes use of both the filtered real-time AVI data and the off-line travel time estimates for estimation of the current and instantaneous travel times in the whole Hong Kong road network while Dion and Rakha's algorithm only adopts the filtered real-time travel time data for estimation of the current travel times on the selected paths with AVI data.

In the proposed RTIS data filtering algorithm, some modifications are made to the Dion and Rakha's algorithm. The objective of such modifications is to filter out the local AVI data reasonably for the Hong Kong road network in order to obtain more accurate travel time estimates. For example, some of the parameters adopted in the proposed algorithm are expressed as sample-size-dependent functions rather than the given constants. As Hong Kong traffic condition is more dynamic than that in US throughout a typical day, the use of sample-size-dependent functions would be more flexible to capture both stable and unstable traffic conditions in Hong Kong.

By using the proposed RTIS data filtering algorithm, the valid real-time AVI data are obtained. The weighted path travel time $t_{\mathrm{AB}\,k}$ from the entry point (tunnel A) to the exit point (tunnel B) at time interval *k* is then computed by the combination of the off-line travel time estimates and the valid real-time AVI data with the use of a weighting factor, $w_{\mathrm{AB}\,k}$, which is shown as follows:

$$t_{\mathrm{AB}\,k} = (1 - w_{\mathrm{AB}\,k})\,\bar{t}_{\mathrm{AB}\,k} + w_{\mathrm{AB}\,k}\;tt_{\mathrm{AB}\,k}\,, \tag{1}$$

where $\bar{t}_{\mathrm{AB}\,k}$ is the off-line average path travel time from A to B at time interval *k* and $tt_{\mathrm{AB}\,k}$ is the mean travel time between A and B obtained by the valid real-time AVI data at time interval *k*. The weighting factor $w_{\mathrm{AB}\,k}$ at the time interval *k* is calculated by equation (2) below. It should be noted that if there is no valid real-time data at the current time interval *k*, $tt_{\mathrm{AB}\,k}$ is then set to be the weighted path travel time for tunnel pair AB at previous time interval *k*-1. In practice, real-time data may not be adequate and/or available for all the links within the study area, the use of the off-line travel time data is therefore important for providing the area-wide coverage in estimation of link travel times.

$$w_{\mathrm{AB}\,k} = \begin{cases} 1-(1-\varphi)^{n_{vk}} & \text{if } n_{vk} > 0 \\ w_{\mathrm{AB}\,k-1} & \text{if } n_{vk} = 0 \end{cases} \tag{2}$$

where n_{vk} is the number of valid AVI data at time interval *k* and φ is a predetermined parameter to be calibrated by the empirical data. With equations (1) and (2), the real-time weighted path travel time $t_{\mathrm{AB}\,k}$ can be obtained and used to estimate the real-time link travel times of the predetermined path on the basis of off-line link travel time estimates. The latter is estimated by an off-line traffic flow simulator (Lam et al., 2002; 2005) together with the corresponding variance and covariance relationships between road links in the study area. The resultant link travel times are the current travel time estimates ($\mathbf{t_d}$) because real-time AVI data from entry point A to exit point B are used for estimation at time interval *k*.

In the proposed RTIS algorithm, the off-line variance-covariance matrix of link travel times $\mathbf{K} = \begin{bmatrix} \mathbf{K_{11}} & \mathbf{K_{12}} \\ \mathbf{K_{21}} & \mathbf{K_{22}} \end{bmatrix}$ is updated by the travel time variances obtained from the valid real-time AVI data. The updated variance-covariance matrix of link travel times is $\hat{\mathbf{K}} = \begin{bmatrix} \hat{\mathbf{K}}_{\mathbf{11}} & \hat{\mathbf{K}}_{\mathbf{12}} \\ \hat{\mathbf{K}}_{\mathbf{21}} & \mathbf{K_{22}} \end{bmatrix}$, where $\hat{\mathbf{K}}_{\mathbf{11}}$ is the updated variance of the travel times corresponding to the links with real-time data, $\hat{\mathbf{K}}_{\mathbf{12}}$ is the updated travel time covariance of the links with and without real-time data, $\hat{\mathbf{K}}_{\mathbf{21}}$ is the updated travel time covariance of the links without and with real-time data, and $\mathbf{K_{22}}$ is the travel time variances corresponding to the links without real-time data obtained from the off-line system.

To update the current travel times ($\mathbf{t_d}$) to the instantaneous travel times on the links with real-time data, the road links are firstly separated into two groups. One group is the closest links (**c**) of the paths to the exit points, while another is the rest of links (**r**) on the predetermined paths. i.e., $\mathbf{t_d} = [\mathbf{t_c}, \mathbf{t_r}]^{\mathrm{T}}$. Using equation (3) (Lam et al., 2002), the instantaneous travel times, $\hat{\mathbf{t}}_{\mathbf{d}}$, on the links with real-time data are estimated and expressed in equation (4). It should be noted that the instantaneous travel times of the closest links of the paths are equal to their current travel times as the travel time delays from these links to the exit points are minimal.

$$\hat{\mathbf{t}}_{\mathbf{r}} = \mathbf{t}_{\mathbf{r}} + \hat{\mathbf{H}}_{\mathbf{rc}}\hat{\mathbf{H}}_{\mathbf{cc}}^{-1}\left(\mathbf{t}_{\mathbf{c}} - \overline{\mathbf{t}}_{\mathbf{c}}\right), \tag{3}$$

$$\hat{\mathbf{t}}_{\mathbf{d}} = [\mathbf{t}_{\mathbf{c}}, \hat{\mathbf{t}}_{\mathbf{r}}]^{\mathrm{T}}, \tag{4}$$

where $\mathbf{t}_{\mathbf{c}}$ and $\mathbf{t}_{\mathbf{r}}$ are the current travel time estimates on the links with real-time data which are separated into two groups **c** and **r**. $\overline{\mathbf{t}}_{\mathbf{c}}$ is the off-line mean travel times of the closest links to the exit points, $\hat{\mathbf{H}}_{\mathbf{rc}}$ and $\hat{\mathbf{H}}_{\mathbf{cc}}$ are the sub-matrices in $\hat{\mathbf{K}}_{\mathbf{11}}$ of the updated variance-covariance matrix of link travel times.

Similarly, the instantaneous travel times on the links without real-time data $\hat{\mathbf{t}}_{\mathbf{e}}$ are also estimated by the following equation (5) (Lam et al., 2002) based on the off-line travel time estimates on the links without real-time data, the updated variance-covariance matrices of link travel times and the instantaneous travel time estimates on the links with real-time data obtained.

$$\hat{\mathbf{t}}_{\mathbf{e}} = \overline{\mathbf{t}}_{\mathbf{e}} + \hat{\mathbf{K}}_{\mathbf{21}}\hat{\mathbf{K}}_{\mathbf{11}}^{-1}\left(\hat{\mathbf{t}}_{\mathbf{d}} - \overline{\mathbf{t}}_{\mathbf{d}}\right), \tag{5}$$

where $\overline{\mathbf{t}}_{\mathbf{e}}$ and $\overline{\mathbf{t}}_{\mathbf{d}}$ are the average link travel times obtained in the off-line system with respect to the road links without and with real-time data, $\hat{\mathbf{t}}_{\mathbf{d}}$ is the instantaneous travel time estimates on the links with real-time AVI data computed by equations (3) and (4), $\hat{\mathbf{K}}_{\mathbf{21}}$ and $\hat{\mathbf{K}}_{\mathbf{11}}$ are the sub-matrices of the updated variance-covariance matrix of link travel time as defined above. The flowchart of the proposed RTIS solution algorithm is displayed in Figure 3. In addition, other real-time data such as GPS data, CCTV images and video detection data can be incorporated in the proposed RTIS algorithm by using some weighted functions with consideration of reliability and sample size of these real-time data.

4. A SURVEY STUDY

Kowloon Central road network is used as a test network in this survey study to demonstrate the performance of the developed RTIS in Hong Kong. In this survey study, the path from the Lion Rock Tunnel (LRT) to the Cross Harbour Tunnel (CHT) was selected for journey time estimation. It is one of the major arterial roads in urban area of Hong Kong. The location of the selected path between LRT and CHT is illustrated in Figure 4. This route was chosen as most of the major roads in Kowloon Central urban area take this path, whereas CHT is the most congested of the three road tunnels connecting Kowloon Peninsula with Hong Kong Island. The total travel distance of the selected path is 6.23 km with free-flow travel time of 6.1 minutes. Travel times are estimated at five-minute intervals during the morning peak (08:00-10:00), inter-peak (14:00-16:00) and evening peak (17:30-19:30) periods of a typical weekday on 26 May 2006 (Friday), for the survey study. Real-time AVI data are collected by tag readers which are installed at the toll plazas of LRT and CHT. Moreover, in order to validate the accuracy of instantaneous travel time estimates on the selected path, a checkpoint located at Homantin (HMT), as shown in Figure 4, was chosen to collect the observed instantaneous travel times from LRT to HMT and from HMT to CHT for the three study periods.

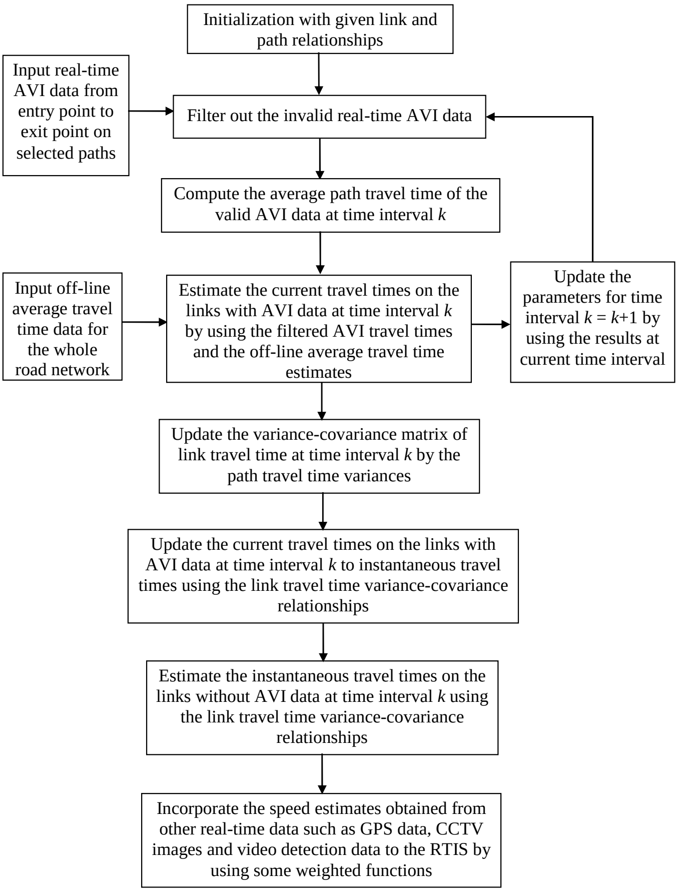

FIGURE 3: Flowchart of the RTIS solution algorithm

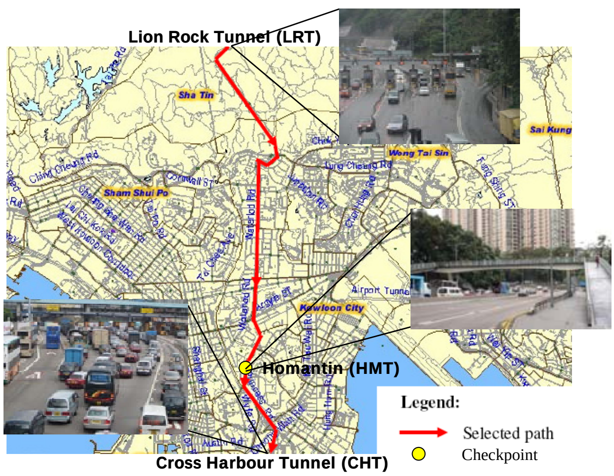

FIGURE 4: Location of the selected path for the survey study

4.1 Manual license plate matching survey

In order to validate the RTIS travel time estimates, observed journey times of all vehicles traveling on the selected path were collected by a manual license plate matching survey carried out in the same time periods on the same day. As aforementioned, there are two types of toll-gates before entering the road tunnels or links in Hong Kong. One type of these toll-gates is mainly for vehicles installed with Autotoll tags and hence the observations from Autotoll tag records are obtained. Another type of toll-gates is used for other vehicles without Autotoll tags, at which there is no toll-tag observation and the license plate readings are recorded by video cameras during the survey periods. Therefore, the combination of toll-tag observations and license plate readings are the total observations at all the toll-gates for a particular road tunnel or link. In the survey study, video recording equipments were set at the toll plazas of LRT and CHT to record the license plate readings of vehicles used manual toll-gates. The license plate readings of vehicles recorded at LRT were then matched with those recorded at CHT using a computer program. The journey times of the matched vehicles traveling from LRT to CHT were then computed for RTIS validation together with the journey times obtained from Autotoll tag records. Similarly, the average observed path travel times from LRT to HMT and from HMT to CHT were also obtained.

The proposed RTIS solution algorithm was applied to the observations collected from the manual license plate survey and Autotoll tag records. The parameters used in the RTIS algorithm are initially recommended by Dion and Rakha (2006) and re-examined with the observation data collected in Hong Kong. The appropriate travel time windows for travel between the survey locations at five-minute interval are determined. Figure 5 demonstrates the travel time window for both of the license plate survey data and the AVI dataset from LRT to CHT by using the RTIS algorithm with the updating interval of five minutes. It should be noted in the RTIS algorithm that observations fall inside the travel time window may not be considered as valid according to the sequence of vehicle entry and exit times on the path. Moreover, there would be a few valid observations outside the travel time window as the proposed solution algorithm allows the third of three consecutive data points that outside the validity window are also considered as valid, provided that all these observations are either above or below the validity window. However, if a fixed threshold of ±20% from the mean travel time is adopted, some of the invalid data identified by RTIS algorithm will become valid and also some valid data in RTIS algorithm are filtered out. It can be seen from Figure 5 that the RTIS data filtering algorithm provides a dynamic travel time window which handles both stable and unstable traffic conditions and functions properly with Hong Kong Autotoll tag data on real-time basis.

Table 2 shows the number of valid observations traveling between these two road tunnels during the survey periods. It should be noted that there were only 1,922 vehicles traveling from LRT to CHT, however, the total traffic flow at each of these two tunnels was greater than 15,000 vehicles during the six-hour survey period. In order to make it clear, the data size for each time period are given in Table 2 with the number of vehicles passing through each of these two tunnels and that traveling from LRT to CHT. It was found that about 40% of the valid observations are installed with tags. Based on the valid observations, the mean travel times for traveling from LRT to CHT are computed at five-minute intervals.

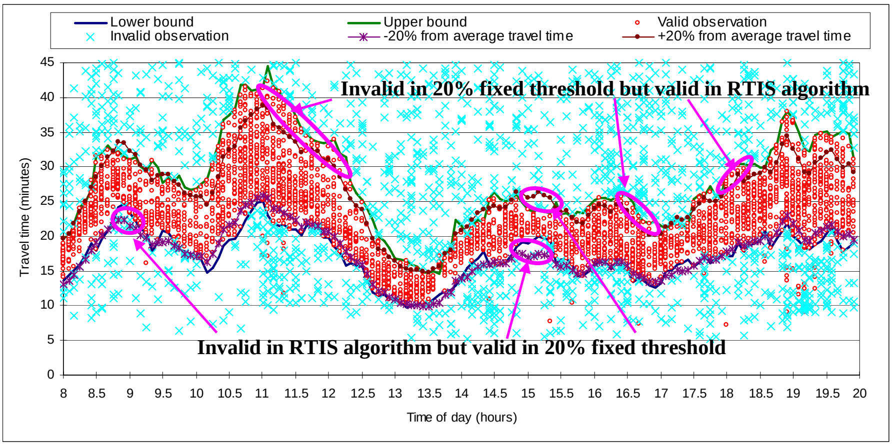

FIGURE 5: Travel time window of the total observations (toll-tags and license plate readings) traveling on the selected path from LRT to CHT

TABLE 2: Number of valid observations obtained during the survey periods*

	CHT	LRT	LRT to CHT		
			Valid observations from Autotoll tags	Valid observations from manual license plate survey	Total
AM peak	6,613	5,362	285	303	588
Inter-peak	6,531	4,735	217	250	467
PM peak	7,029	5,643	259	608	867
Total	20,173	15,740	761 (39.59%)	1,161 (60.41%)	1,922 (100%)

* Survey periods are 08:00-10:00, 14:00-16:00 and 17:30-19:30 on 26 May 2006 (Friday).

4.2 Evaluation results

4.2.1 Comparison of current travel time estimates by the four AVI algorithms

In order to evaluate which AVI algorithm is most applicable for Hong Kong under various traffic conditions during peak and non-peak periods, the same set of observation data is used to validate the results of different algorithms. The four AVI travel time algorithms (RTIS, TransGuide, TranStar and Transmit) are used to estimate the current travel times from LRT to CHT which is the southbound traffic of the selected path. The estimated current travel times by each algorithm are then compared with the observed travel times for three survey periods, 08:00-10:00 (AM peak), 14:00-16:00 (inter-peak) and 17:30-19:30 (PM peak), respectively. The comparisons are shown in Figures 6, 7 and 8 for the AM, inter-peak and PM periods respectively together with the absolute errors and the absolute percentage errors at five-minute interval, which are the measures for validating the accuracy of estimates of these four algorithms.

The RTIS is superior to the TransGuide, TranStar and Transmit algorithms on the basis of the validation results at five-minute interval. It can be seen in Figures 6, 7 and 8 that the average path travel times estimated by the proposed RTIS algorithm are the most closest to the observed travel times for all the three study periods. Moreover, the absolute errors and the absolute percentage errors are the least on the RTIS current travel time estimates for both peak and inter-peak periods. For example, as shown in Figure 6, the maximum absolute errors at five-minute interval are 2.62, 3.79, 3.28 and 5.73 min, respectively, for the RTIS, TransGuide, TranStar and Transmit algorithms during AM peak period. The maximum absolute percentage error of the RTIS algorithm is 11.55% whereas the other three algorithms are 16.69%, 15.23% and 23.95% during AM period. Both the maximum absolute error and the maximum absolute percentage error of the RTIS current travel time estimates are lower than those of the other three algorithms. It is clear from the results that the performance of the Transmit algorithm is worse than other three algorithms. The maximum absolute percentage errors of the Transmit algorithm are double of the RTIS algorithm's. It may be due to the longer updating interval (with 15 minutes each) for the validity window in Transmit algorithm. However, the performances of TransGuide and TranStar algorithms are similar.

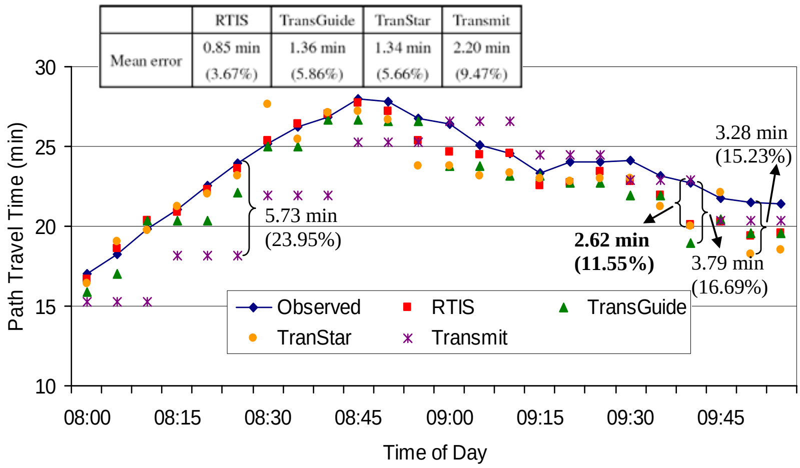

FIGURE 6: Current travel time estimates on the selected path from LRT to CHT during AM peak period (08:00-10:00)

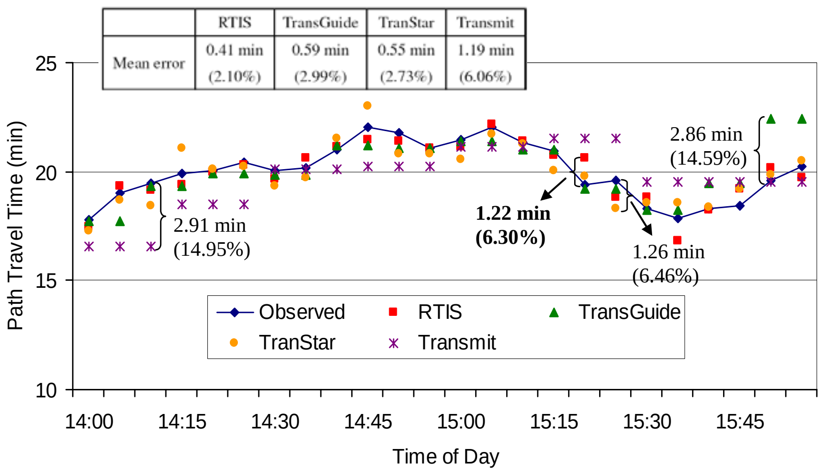

FIGURE 7: Current travel time estimates on the selected path from LRT to CHT during inter-peak period (14:00-16:00)

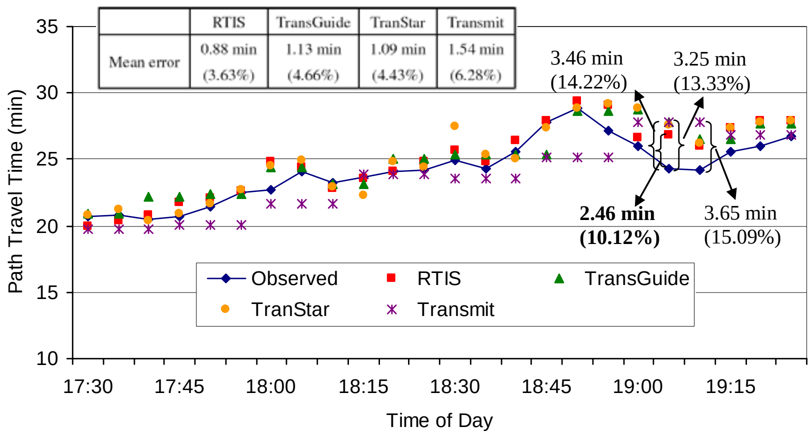

FIGURE 8: Current travel time estimates on the selected path from LRT to CHT during PM peak period (17:30-19:30)

In terms of the mean absolute errors and the mean absolute percentage errors, the performance of RTIS algorithm is also the best among the four algorithms for the three study periods. It is also noted that the errors in the peak periods are larger than those in the non-peak period. For example, the mean absolute errors are 0.85, 0.41, 0.88 min and the mean absolute percentage errors are 3.67%, 2.10%, 3.63% in the RTIS algorithm during AM, inter-peak and PM periods, respectively. The errors of the travel time estimates for AM and PM peak periods are more or less the same; however, the errors for inter-peak period are only half of those for AM and PM peak periods. Similar results are also found in the other three algorithms. This indicates that the travel time estimation of all these four algorithms performs generally better under the un-congested condition than the congested condition.

4.2.2 Instantaneous travel time estimation on the road sections with real-time AVI data

The instantaneous travel time estimates are validated against the observed instantaneous travel times from LRT to HMT and from HMT to CHT for the three study periods. The results of the instantaneous travel time estimation are plotted in Figure 9. It can be observed in Figure 9 that most of the data points are close to the 45° line (i.e. the line represents the equality of estimated and observed instantaneous travel times). The coefficient of determination (R^2) which reflects the accuracy of the estimation is 0.89. This means that 89% of estimated travel times are well fitted with the observed travel times for the two road sections. The average absolute errors are also found to be 5.64% and 5.21% for the road sections from LRT to HMT and from HMT to CHT, respectively. Although the accuracy of instantaneous travel time estimation is slightly lower than that of current travel time estimation, the performance of the RTIS is still satisfactory with the average estimation errors of less than 10% throughout the three study periods.

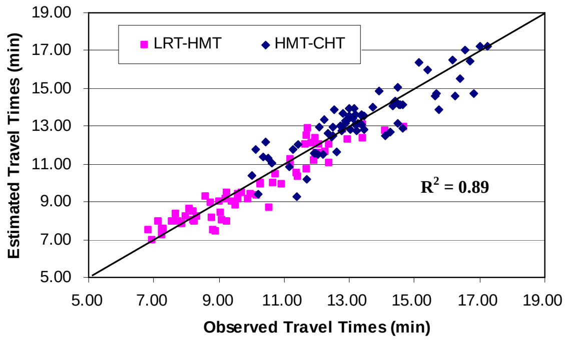

FIGURE 9: Accuracy of instantaneous travel time estimation on the road sections from LRT to HMT and from HMT to CHT

4.2.3 Instantaneous travel time estimation on the road section without real-time AVI data

In the survey study, an Autotoll tag reader has also been installed at the selected checkpoint HMT to collect additional real-time AVI data. An experiment is conducted to demonstrate the instantaneous travel time estimation on the road section without real-time AVI data. In this experiment, only real-time AVI data from HMT to CHT are input to the system and so the real-time data are not available on the road section from LRT to HMT. The results are then compared with the observed instantaneous travel times from LRT to HMT. The mean absolute errors and the mean absolute percentage errors are shown in Table 3. As expected, the instantaneous travel time estimates on the road section without the AVI data are less accurate than those on the links with AVI data. However, the results are still acceptable with the average absolute errors of around 15% throughout the three study periods.

TABLE 3: Mean absolute errors and absolute percentage errors for the instantaneous travel time estimates on the road section from LRT to HMT

	AM peak	Inter-peak	PM peak	Overall three study periods
Mean absolute error	1.98 min	1.08 min	1.36 min	1.49 min
Mean absolute percentage error	17.57%	11.78%	12.88%	**14.18%**

5. GIS-BASED RTIS WEBSITE PORTAL

In order to disseminate up-to-date geo-referenced traffic information to road users, a GIS-based website portal is developed for presentation of the RTIS results. In this website portal, the users can access to various real-time traffic information such as average traffic speed on road links, the shortest path for a selected origin-destination pair together with the corresponding path travel time. The link speed information is derived from the link length and the instantaneous link travel time estimates. Such traffic information is updated at five-minute intervals and the latest results are shown on the website portal. This RTIS has already been subscribed by Hong Kong Transport Department. A real-time speed map for the main routes in Hong Kong North, Kowloon and New Territories South areas, shown in Figure 10, has been launched on Transport Department's website since January 2007 (http://rtis.td.gov.hk/rtis). In the RTIS speed map, the speeds of the links with real-time AVI data available are considered as directly deduced traffic speeds, whereas the speeds of the links without real-time data are indirectly deduced traffic speeds. Real-time CCTV images are also provided in the speed map.

FIGURE 10: RTIS speed map (Source: Hong Kong Transport Department, http://rtis.td.gov.hk/rtis)

6. CONCLUSIONS

In this paper, a GIS-based real-time traveler information system (RTIS) for Hong Kong has been presented. A novel solution algorithm has been proposed for estimating both the current and instantaneous travel times in Hong Kong, with making use of the real-time AVI data and the off-line travel time estimates by the traffic flow simulator. In the RTIS, an enhanced travel time estimation algorithm has been adapted for addressing the shortcomings of the current state-of-the-art algorithms. Unlike the other existing AVI algorithms, the RTIS estimates the travel times on both road links with and without real-time data. Validation of the RTIS estimates has been carried out by using the empirical data collected from a manual license plate matching survey on the selected path between Lion Rock Tunnel and Cross Harbour Tunnel during morning peak, inter-peak and evening peak periods of a typical weekday. The validation results show that the RTIS solution algorithm is superior to the other three existing AVI algorithms (i.e. TransGuide, TranStar and Transmit algorithms) on the basis of the same set of empirical data collected in Hong Kong. It was found that both the absolute errors and the absolute percentage errors are the least on the current travel times estimated by the proposed RTIS algorithm for the three study periods. Moreover, the estimations of instantaneous travel times on the road sections with and without real-time AVI data have been illustrated. The validation results show that the performance of RTIS is satisfactory and acceptable.

Enhancement of the RTIS algorithm is being carried out by incorporating GPS data to update the off-line travel time estimates particularly on the links without AVI data. Sensitivity tests will be conducted to investigate the effects of other factors such as location, level of service, and weather on the RTIS estimates. The off-line travel time database will also be updated with taking into account the effects of adverse weather forecasts in a road network for short-term travel time forecasting. Moreover, appropriate number and locations of AVI readers will be determined in order to enhance the accuracy of travel time estimation. Incident detection will also be incorporated into the system for further enhancement. In addition, further study will be conducted to disseminate the RTIS results to public via 3-G cellular telephones.

ACKNOWLEDGMENTS

The authors wish to thank the Autotoll Limited and the Transport Department of the Government of the Hong Kong Special Administrative Region for the permission to use Figures 2 and 10 in the paper. The work described in this paper was collaborated with Autotoll Limited and jointly supported by research grants from the Research Committee of The Hong Kong Polytechnic University (Project Nos. 1-ZE10 and 1-BBZG).

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