Using Archived ITS Data to Generate Improved Freeway Travel Time Estimates

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ABSTRACT

Accurate travel time estimation has become possible with the deployment of advanced traveler management and information systems. Dynamic message signs, websites, and handheld/in-vehicle devices are being increasingly used by public agencies to communicate important travel information to the public such as incidents, road closures and travel times. Travel time estimates are usually derived from roadway sensors, although other technologies such as cell phone matching, license plate matching, automatic vehicle identification and video detection have also been employed. In Oregon, freeway travel time estimates are generated by the Oregon Department of Transportation using data from inductive loop detectors throughout the Portland metropolitan area. These estimates are generated using a simple midpoint algorithm that extrapolates measured speeds over a freeway segment. The objective of this paper is to evaluate the accuracy of the current midpoint algorithm by comparing the derived estimates to ground truth (probe vehicle) travel times. In addition, travel time estimates from a travel time algorithm developed by Coifman were also evaluated for accuracy under varying traffic conditions. Various scenarios were tested using traffic data from both upstream and downstream detector stations. The results indicate that both the midpoint and the Coifman algorithms generate accurate travel time estimates under free flow conditions. The Coifman algorithm using data from the upstream detector provided the best estimate of travel time for a link during congestion as well as in periods after an incident occurred.

INTRODUCTION

An important component of the management of the transportation system is the delivery of pre-trip or en-route travel information to the public in order to enable them to make informed travel choices. With reliable information, travelers can adjust their travel time, mode and route. This information should include travel time; it is relatively easy to report “current” travel time on instrumented freeways. It is more difficult to report arterial travel time and to forecast future travel times on network segments at times when travelers actually reach a particular segment. Thus, the accurate estimation of travel time has become critical with the advent, deployment, and maturation of advanced traveler information systems.

Travel time information is delivered to the public through devices such as desktop PCs, handheld phones or PDAs, in vehicle displays, highway advisory radio or dynamic message signs. Travel time estimates are derived using techniques such as license plate matching, video imaging, cell phone tracking, automatic vehicle identification (AVI) as with electronic toll tags, automatic vehicle location (AVL) as with GPS tracking systems, and fixed sensors such as inductive loop detectors (*1*). Generating travel time estimates from fixed point sensors is the most common method in the U.S. Travel time estimates from dual loop detectors that directly measure speed are inherently more accurate because estimating travel time from single loop detectors involves making assumptions about vehicle length to calculate speed. Past research has proved that this assumption leads to higher inaccuracies (*3*,*4*).

There are approximately 502 double loop detectors on the freeways in the Portland, Oregon metropolitan area. These detectors, located in each freeway lane and on 138 metered on-ramps, report count, speed and occupancy every 20 seconds and this information is transmitted to the Traffic Management Operations Center (TMOC). Detectors are spaced an average of 1.24 miles apart on the 140 directional miles of freeway in the region. A number of algorithms have been developed by researchers to estimate travel time from single loop detectors (*5*,*6*). The Oregon Department of Transportation (ODOT) provides real time traffic information through several dynamic message signs (DMS) at key decision points on the network and through the web (tripcheck.com). As shown in Figure 1, ODOT provides a range of travel time in minutes (e.g. 10-12 minutes) to a particular junction. Under congested conditions the time range increases, and under very congested conditions due to an incident, for example, the message will read INCIDENT. Travelers can also obtain vital information through their mobile phones by dialing 511. In order to generate real time travel time estimates on highways, ODOT employs a simple midpoint algorithm that extrapolates measured speeds over each freeway segment. The goal of this paper is to evaluate the accuracy of the midpoint algorithm and that developed by Coifman (*2*) compare the travel time estimates with ground truth (probe vehicle) estimates under varying traffic conditions. The overall objective of our travel time study is the identification and/or development of a travel time algorithm that is able to generate accurate travel time estimates especially during congested periods as well as during the occurrence of incidents.

The remainder of this paper is divided into four sections. A brief literature review follows this section, followed by description of the data sources and the study site. Analysis of the travel time estimates produced by the different algorithms is described followed by conclusions and some recommendations.

BACKGROUND

Calculating speeds from loop detectors and extrapolating those speeds over a freeway segment to determine a segment travel time involves assumptions about vehicle length and calculating speed based on relationships between flow, occupancy and vehicle length. Past research by Hall and Persaud (*3*), and Pushkar, Hall and Acha-Daza (*4*) indicates that the accuracy of the speed estimates derived from an assumed value of vehicle length is poor, which in turn leads to less accurate travel time estimates. Recent studies have focused on improving the accuracy of estimated travel time from single loop detectors (*5*, *6*).

Dailey (*5*) used a stochastic approach and a Kalman filter to estimate speed and derived travel time using the speed estimate. However, this method requires estimation of several parameters. Petty et al. (*6*) assume that within a certain time frame, travel times follow the same probability distributions. Cortes et al.(*1*) derive travel times assuming that the representative travel time for a certain link is the travel time of the vehicle that reaches the midpoint of the link at the midpoint of the time interval. Coifman (*2*) postulates that a vehicle’s travel time across a link is the time taken for the vehicle’s trajectory to propagate across the link.

The algorithm proposed by Coifman uses basic traffic flow principles to estimate the travel time of a trajectory across a link. The travel time is estimated knowing the vehicle’s velocity, the headway between the vehicles and congested wave velocity. This algorithm uses successive speed readings to build the trajectory of the vehicle in order to calculate travel time. Coifman’s algorithm has been tested with individual vehicle trajectory data but its usefulness in an environment with vehicle count and speed data aggregated over short time intervals (e.g., 20 or 30 seconds) was mentioned by Coifman (*2*), but has not been extensively tested.

The midpoint algorithm used by ODOT is currently used to provide real time travel time estimates. The algorithm computes travel time as a ratio of distance to speed, using influence areas upstream and downstream of each detector. ODOT establishes influence areas at the midpoint between two detectors along a directional freeway segment. Due to the availability of a regional ITS data archive it was possible to design a customized user interface for testing various travel time algorithms. For this study, travel time estimates were generated using ODOT’s midpoint algorithm using archived ITS data were then compared to ground truth travel time data extracted from probe vehicle runs. (*8*) In addition, these travel time estimates were further compared with travel times generated by several versions of the algorithm developed by Coifman.

STUDY AREA AND DATA

In previous study, travel time estimates derived from the midpoint algorithm were compared to the probe travel times for the links shown in Figure 1 (*8*). This current study builds on the earlier work by evaluating additional algorithms in addition to the midpoint algorithm. A subset of nine links were chosen from the previous study to further evaluate the performance of ODOT’s standard midpoint algorithm and several variations of the one developed by Coifman. The summary of probe vehicle runs, including the link number, the length of each link in miles and the average detector spacing, and the number of probe vehicle runs for each analyzed link are shown in Table 1.

Figure 1 shows the locations of the links. These links were chosen on the basis of availability of ground truth probe vehicle data and high traffic flows and congestion during peak periods. Travel time estimates were computed for Links 3, 4, 5, 6, 8, 9, 10, 12 and 13. Links 3, 4, 5, 6 covered portions of I-5, whereas links 8 and 9 represented OR-217. Links 10 and 12 represented I-205 and link 13 stood for I-84 E.

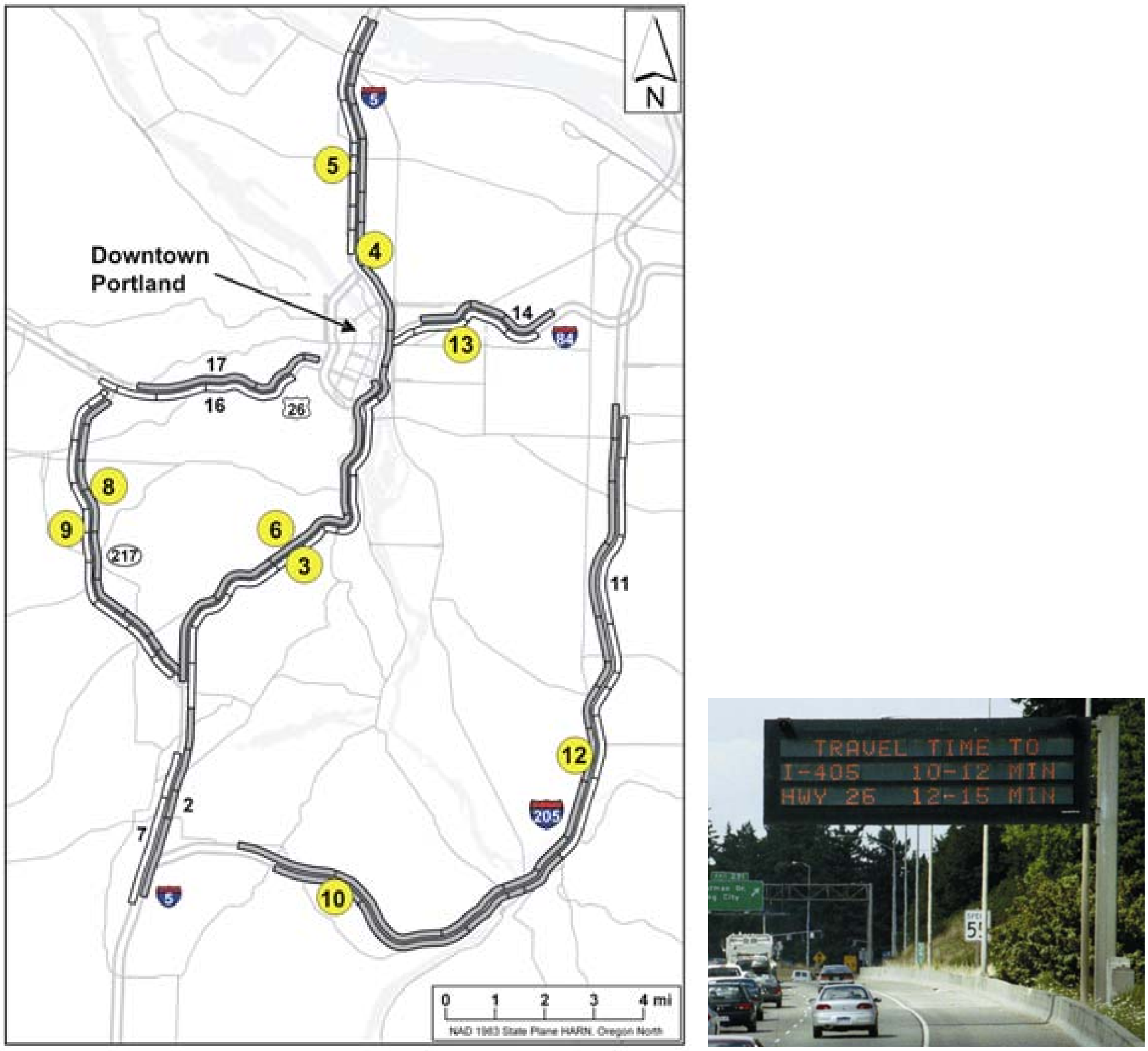
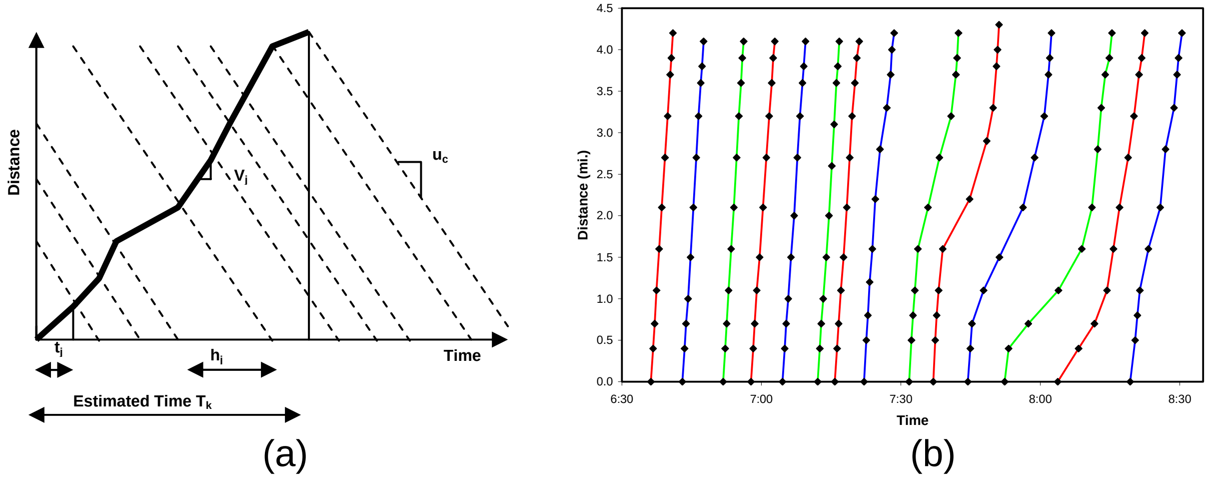


FIGURE 1 Site map, influence areas for midpoint algorithm and ODOT VMS.

Three data sources were used in this study. As part of the Portland region's Advanced Traveler Managed Systems (ATMS), the ODOT Region 1 Traffic Management Operations Center (TMOC) maintains a fiber optic communication system linking all 502 inductive loop detectors. These detectors report count, occupancy, and speed in each freeway lane, and count from the on-ramps every 20 seconds. These data are fed into the Portland Oregon Regional Transportation Archive Listing (PORTAL—see http://portal.its.pdx.edu), a database that was developed at Portland State University based on the Archived Data User Service (ADUS) framework for archiving intelligent transportation systems data. PORTAL provides an extensive and valuable data set that can be used for improved performance assessment and modeling (*7*). A customized travel time functional area was set up in PORTAL to generate travel time estimates from archived loop detector data using the ODOT midpoint and the Coifman algorithms. The project would have been much more difficult without the PORTAL system.

Travel time estimates generated from PORTAL's archived loop data were compared with two sets of ground truth data. Probe vehicle data (87 runs) were collected during April–May 2005 for selected links of the Portland freeway network by researchers at Portland State University (*8*). A total of 15 hours of data, over 516 miles of travel over 7 days were collected. A statistical analysis was conducted to ensure that sufficient numbers of runs were performed. Typical probe vehicle headway ranged between 5-7 minutes. Travel time data for all the freeway links were collected using global positioning systems (GPS) devices. Custom software (ITS-GPS) developed specifically for use with Palm handheld computers and the GPS devices were used to record the position of each probe vehicle every 3 seconds. These data streams could also be used to calculate speed and distance traveled (*9*).

In addition to the probe vehicle data from 2005, transit probe data was provided by TriMet for bus routes 95 and 96, which are express routes running on the freeway. Nine days of the northbound runs for route 96 were analyzed in this study. The route traced I-5 N between OR-217 and I-405 interchange can be represented by Link 3, shown in Figure 1. The TriMet buses are equipped with an AVL system that also archives detailed stop-level activities (*10*). For a three week experiment in November 2002, TriMet's buses were programmed to record arrival times for "pseudo stops" located at fixed, designated points on the freeway, since buses do not stop on the freeway. The data from TriMet for these virtual detectors for northbound route 96 consisted of 148 runs and contained an arrival time and a leave time for each "pseudo stop" along with the distance traveled from the start to the end of the trip. Figure 2 shows the sample trajectories from Nov 7, 2002. These trajectories represented route 96, which traversed a section of I-5 N, just south of downtown Portland. The pseudo stops are indicated on each of the trajectories with a marker.



(a) (b)

FIGURE 2 Sample TriMet bus trajectories and Coifman algorithm travel time estimation.

METHODOLOGY

Travel time estimates from the archived loop detector data were generated using a standard midpoint algorithm and one developed by Coifman. The algorithm proposed by Coifman uses traffic flow theory to estimate travel times for a link (*5*). Coifman proposed that the velocity of a vehicle can be represented by:

$$v(x,t) = f(x + u.t) \tag{1}$$

where x is the distance, t is time and u can be either u_f the free flow signal velocity or u_c the congested signal velocity. The vehicle trajectories in a time space diagram can be represented by the differential equation:

$$\frac{dx}{dt} = v(x,t) \tag{2}$$

The vehicle's travel time across a link is the time taken by the corresponding trajectory to travel across the link and is shown in Figure 3. Travel time for a link can be estimated using vehicle velocity (v_j), headway (h_j) and congested signal speed using the relationship:

$$\tau_j = \frac{h_j}{1 + \frac{v_j}{u_c}} \tag{3}$$

$$x_j = v_j \tau_j \tag{4}$$

The value for shock wave speed congested conditions (u_c) was assumed to be constant at 14 mph based on Coifman's assumption (*2*). Since the loop data from ODOT is available at the 20 second level, the headway (h_j) for this study is assumed as 20 seconds. Using the velocity (v_j) from the loop data and using equations (3) and (4), t_j and x_j can be calculated. The successive x_js are added to obtain the link distance and the sum of t_j 's yields the total travel time for the link. For the k-th vehicle, the largest Nk is given by equation 5

$$d \geq \sum_{j=k}^{k+N_k} x_j \tag{5}$$

d represents the length of the link and N_{k+1} is the estimate of the number of vehicles that pass the detector while the k-th vehicle is traversing the link. However, the total distance obtained can exceed the link distance. Therefore, to accurately estimate the link distance, a weight *p* is calculated as shown in equation 6:

$$p = \frac{\left(x_{k+N_k+1} + \sum_{j=k}^{k+N_k} x_j \right) - d}{x_{k+N_k+1}} \tag{6}$$

Finally travel time is estimated as:

$$T_k = p.\tau_{k+N_k+1} + \sum_{j=k}^{k+N_k} \tau_j \tag{7}$$

These equations were coded into PORTAL for use with archived loop detector data and Coifman travel time estimates were produced every 20 seconds for selected links. These travel time estimates were evaluated for accuracy by comparing them to the ground truth estimates.

Figure 3a displays the mechanism of ODOT's midpoint algorithm currently used for travel time estimation and for dynamic message sign display. Each detector has an influence area as shown in Figure 3a. It is assumed that the detector station is at the midpoint of each influence area. Travel time for each segment is calculated as the ratio of the segment length to measured speed. Travel time is estimated for each segment at each 20-sec interval and aggregated over the entire link. In order to compare travel times over the same distances, the starting and ending mileposts for each link were noted from the probe vehicle data and the estimated travel times were computed over the same distance. The start time of each probe vehicle run was matched to the nearest prior 20 second reading in PORTAL. The travel time estimated at the nearest prior 20 second interval was taken as the travel time for the link.

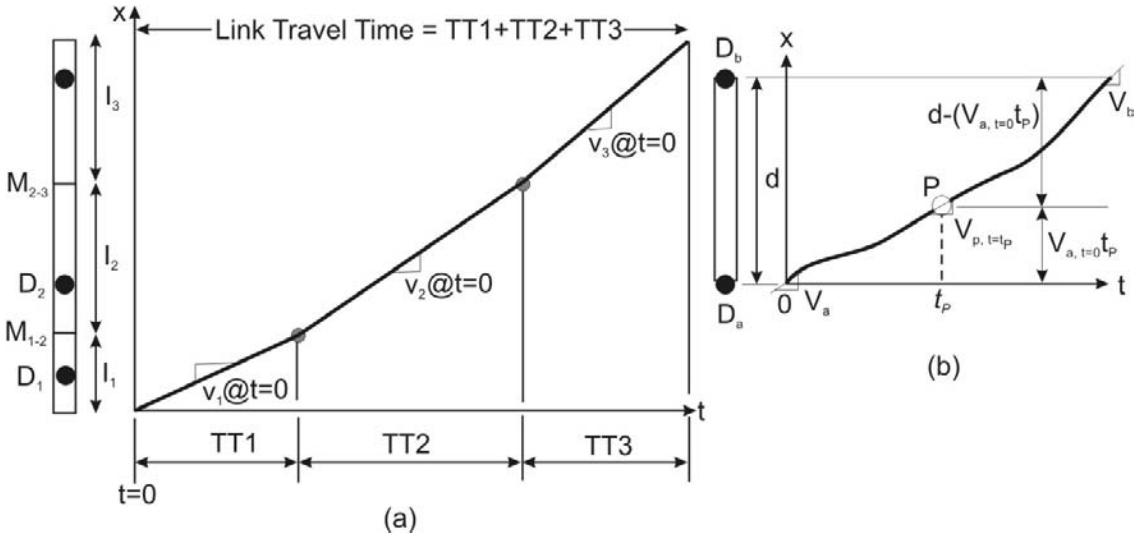


FIGURE 3 Midpoint algorithm travel time estimation.

Six scenarios were tested using the Coifman and midpoint algorithms. The Coifman algorithm was evaluated using either upstream or downstream speeds or a combination of both. The midpoint algorithm was tested in its standard form as well as taking an average of the upstream and downstream detector speeds to generate travel time estimates. These six methods were run on the archived loop detector data in PORTAL and travel time estimates were produced. These estimates were then compared to the ground truth data. These six different are explained below with the help of Figure 3b. A hypothetical link of distance *d* is represented in Figure 3b with upstream detector *a* and speed V_a and downstream detector *b* and speed V_b. A hypothetical vehicle is assumed to travel along the link and is leaves upstream detector A at time t=0 and is at position *P*, somewhere along the link at time t=t_P.

The six different methods that were tested are:

- Coifman algorithm using speeds from upstream detectors only: $V_{P,t=t_P} = V_{a,t=t_P}$
- Coifman algorithm using speeds from downstream detectors only: $V_{P,t=t_P} = V_{b,t=t_P}$
- Coifman algorithm using speeds from both upstream and downstream detectors using the midpoint influence areas:
  - $V_{P,t=t_P} = V_{a,t=t_P}$ while $V_{a,t=t_P} t_P < d/2$
  - $V_{P,t=t_P} = V_{b,t=t_P}$ while $V_{a,t=t_P} t_P > d/2$
- Coifman algorithm using speeds from upstream and downstream detectors weighted in the ratio of distance of the hypothetical vehicle from each detector: $V_{P,t=t_P} = \dfrac{[V_{a,t=t_P} \times (d - V_{a,t=t_P} t_P)] + [V_{b,t=t_P} \times (V_{a,t=t_P} t_P)]}{d}$
- Midpoint algorithm: $V_{P,t=t_P} = V_{a,t=t_P}$ or $V_{P,t=t_P} = V_{b,t=t_P}$ depending on the influence area.
- Midpoint algorithm using speed at time (t = 0) that is an average of the upstream and downstream detector readings: $V_{P,t=t_P} = \dfrac{V_{a,t=t_P} + V_{b,t=t_P}}{2}$

ANALYSIS

The Coifman and the midpoint algorithms were estimated on archived ITS data from two different time periods. Travel time estimates were derived using the algorithms on archived loop detector data for specific days in 2005 and these estimates were compared to the probe vehicle travel times. In addition, travel times estimated on archived loop data from November 2002 were also compared to the TriMet bus probe travel times.

Probe Vehicle Data Analysis

Mean travel times (and standard deviations) for the probe vehicle and the mean estimates obtained from the Coifman and Midpoint algorithms are shown in Table 1 and Figures 4 and 5 . The Coifman algorithm was implemented using speed readings from the upstream as well as downstream detectors and these travel time estimates are shown in Table 1.

TABLE 1 Probe, Coifman and Midpoint Travel Time Statistics

No.	Distance	Spacing	No.	Probe		Coifman (u/s)			Coifman (d/s)			Midpoint		
	mi	*mi*	**Runs**	*μ*	*σ*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*
3	7.52	1.07	6	8.33	0.31	8.32	0.44	0.18	9.69	1.58	2.09	8.99	0.50	0.92
4	5.40	1.08	5	14.08	5.91	12.71	5.96	1.43	13.96	4.22	2.35	15.10	8.73	2.84
5	4.00	0.57	4	5.95	2.41	6.39	2.90	0.66	5.77	1.75	0.62	6.61	2.79	0.74
6	5.89	1.96	9	6.99	0.51	7.64	2.18	1.88	6.43	0.09	0.71	7.65	1.95	1.69
8	5.95	0.74	7	18.82	10.53	15.61	8.39	4.00	11.90	4.80	8.75	17.55	11.17	6.02
9	6.32	0.70	4	7.11	0.60	6.41	0.32	0.76	6.96	0.38	0.32	6.50	0.12	0.81
10	5.90	1.48	4	12.73	0.99	14.16	0.33	1.57	13.48	1.05	0.82	14.84	4.97	4.42
12	16.39	1.26	4	17.29	0.54	17.66	0.11	0.59	16.96	0.11	0.53	17.15	0.18	0.44
13	3.70	1.06	11	4.92	2.26	4.93	2.09	0.38	4.63	1.58	0.76	4.93	2.01	0.64

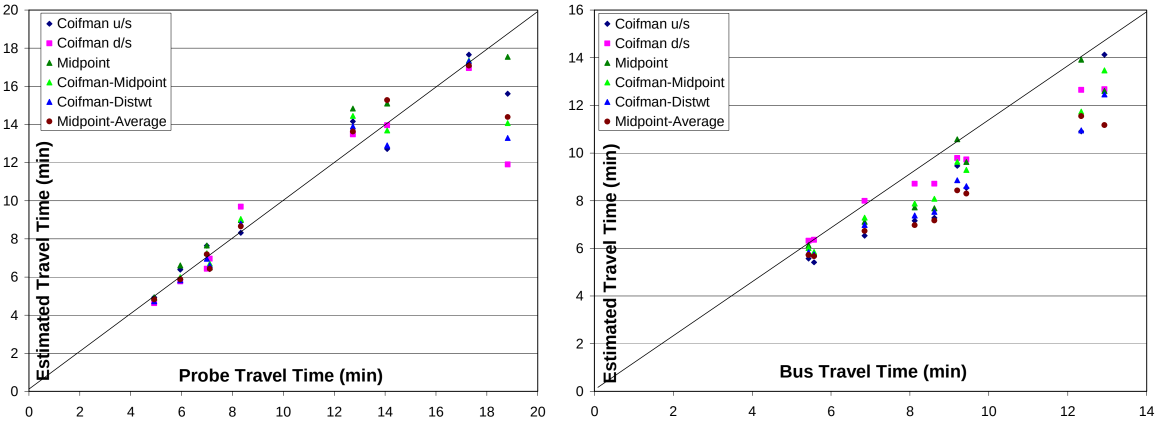
From the table it is apparent that both the Coifman and Midpoint algorithms generate reasonably accurate travel time estimates. The root mean square error, which represents the error between the algorithm generated travel time estimates and the probe vehicle travel times, in almost all cases was lowest for the Coifman u/s travel time estimates. The root mean square was computed for each link by calculating the difference in between the probe vehicle travel times and the estimated travel times for each run. These individual errors were squared and summed and divided by the number of individual errors. Finally, the square root was taken and the root mean square error for each link was produced. The travel time estimates from Table 1 also indicate that the Coifman algorithm (u/s or d/s) produces more accurate travel time estimates than the midpoint algorithm as indicated by the lower root mean square error. The type of Coifman algorithm (u/s or d/s) that generates more accurate travel time estimates depends on the location and formation of queue with respect to the detector. If the queue forms closer to either detector, then the travel time estimates using readings from that detector will tend to be more accurate. However if the queue forms at the midpoint of the link, then using readings exclusively from the upstream or downstream detectors may not produce accurate travel time estimates. In such cases, it may be beneficial to implement the Coifman algorithm using a combination of speed readings from the upstream as well as downstream detectors.

TABLE 2 Travel Time Statistics

No.	**Probe**		**Coifman - Midpoint**			**Coifman – Distwt**			**Midpoint - Average**		
	μ	*σ*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*
3	8.33	0.31	9.04	1.10	1.37	8.80	0.54	0.80	8.66	0.26	0.47
4	14.08	5.91	13.69	4.45	1.61	12.90	4.22	2.05	15.28	10.94	4.72
5	5.95	2.41	5.99	2.20	0.24	5.83	2.01	0.41	5.88	1.83	0.51
6	6.99	0.51	7.25	1.37	1.01	6.96	0.95	0.63	7.19	1.26	0.95
8	18.82	10.53	14.07	6.92	5.96	13.29	6.15	6.94	14.39	7.20	5.85
9	7.11	0.60	6.70	0.36	0.50	6.62	0.33	0.57	6.43	0.09	0.87
10	12.73	0.99	14.45	0.50	1.80	13.90	0.64	1.25	13.63	3.28	2.69
12	17.29	0.54	17.35	0.16	0.46	17.32	0.12	0.44	17.09	0.18	0.46
13	4.92	2.26	4.90	2.02	0.44	4.72	1.81	0.53	4.83	1.92	0.64

Table 2, shows the travel time estimates generated by the Coifman algorithm using the midpoint influence areas. Travel time estimates were also generated using the speeds from both the upstream and downstream detectors weighted by distance from each respective detector. Therefore if the hypothetical vehicle is closer to the upstream detector, the speed from the upstream detector is given more weight. As the vehicle approaches the end of the link, the speeds from the downstream detector influence the vehicle more than the speeds from the upstream detector.

Travel time estimates from the algorithms are compared to the ground truth data in Figure 4. For the probe vehicle data, travel times are fairly well estimated except for Link 8 travel times seen at the far right end of the graph. Travel time estimates compared to the bus travel times were generally underestimated as seen from Figure 4 (b).



(a) Probe Vehicles **(b) Bus**

FIGURE 4 Probe vehicle and bus travel time estimate comparisons.

Figure 5 shows the mean probe travel times for each link along with the estimates derived from the algorithms. The variance in travel times is also represented as an error bar in Figure 5.

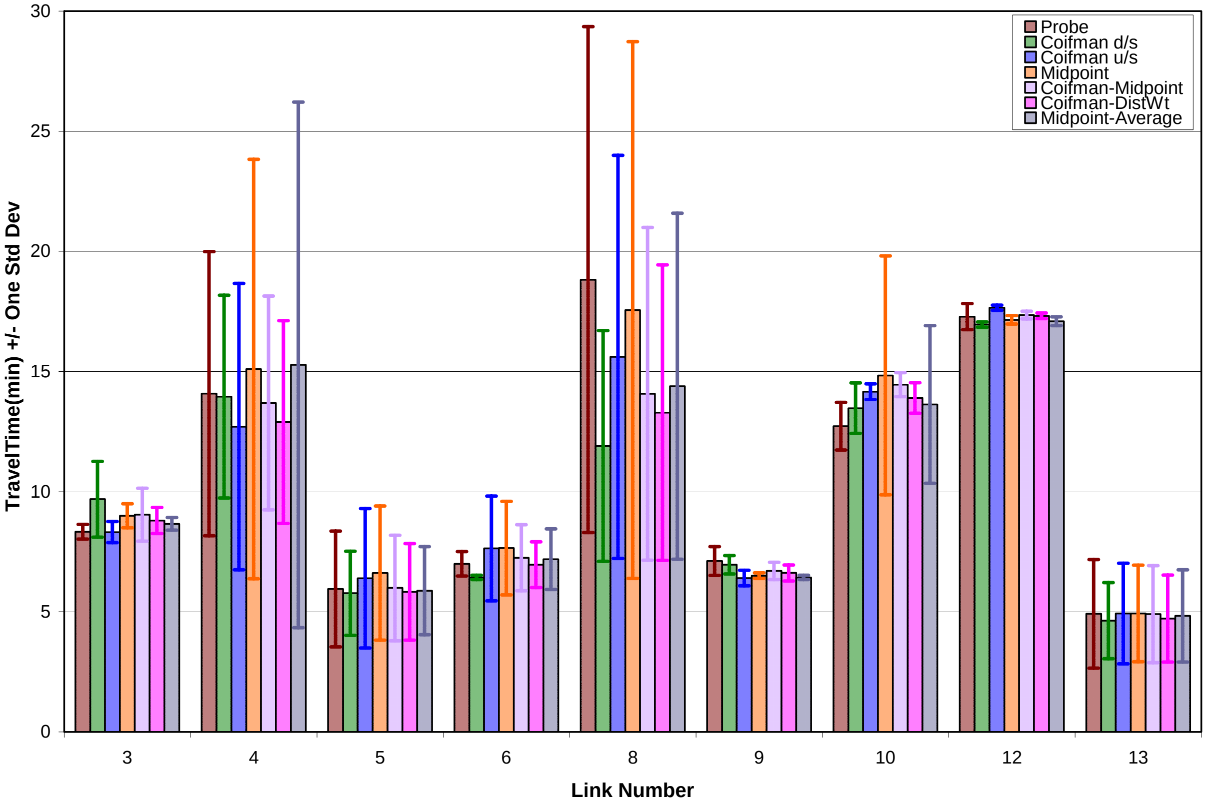


FIGURE 5 Probe vehicle travel time estimate and variance comparisons.

The largest amount of error was encountered for Link 8 travel time estimates. This was a result of the probe vehicles encountering an incident during the travel time runs on Link 8. In order to study the performance of the algorithms in depth, time space plots were constructed for varying traffic conditions. These included free flow conditions, occurrence of incident and large detector spacing. Any travel time algorithm that is employed to produce travel time estimates needs to be robust and sensitive to varying traffic conditions.

Free Flow Travel Times

Probe vehicle, Coifman (u/s and d/s) and Midpoint time space trajectories were constructed for travel time runs that encountered free flow conditions. The Coifman (u/s and d/s) and the midpoint trajectories track the probe vehicle trajectory closely. Therefore, during free flow conditions, the travel time estimates generated by the Coifman and the midpoint algorithms are accurate.

Incident Travel Times

The effects of incidents on travel conditions (travel time and delay) are difficult to predict. The travel time estimates for Link 8, where the probe vehicles encountered an incident were subject to large errors. To further understand the reason for the high margin of error, probe vehicle, Coifman and midpoint trajectories were plotted for one of the runs on Link 8 and these are shown in Figure 6. The trajectories were constructed by plotting the time taken or estimated to travel from one detector station to the next against distance between the detectors.

The dashed horizontal lines represent detector locations. The Coifman and the midpoint trajectories follow the general shape of the probe vehicle trajectory. The Coifman algorithm using the upstream detector speeds generates the most accurate travel time estimate for this run. However, all the algorithms show large errors in the estimation of travel time when incidents are encountered. Therefore, any algorithm that is used for travel time estimation needs to incorporate the ability to handle incidents and predict travel times accurately especially after the incident has occurred. The accurate prediction of travel time can assist the travelers in choosing alternate routes and minimizing the total system delay.

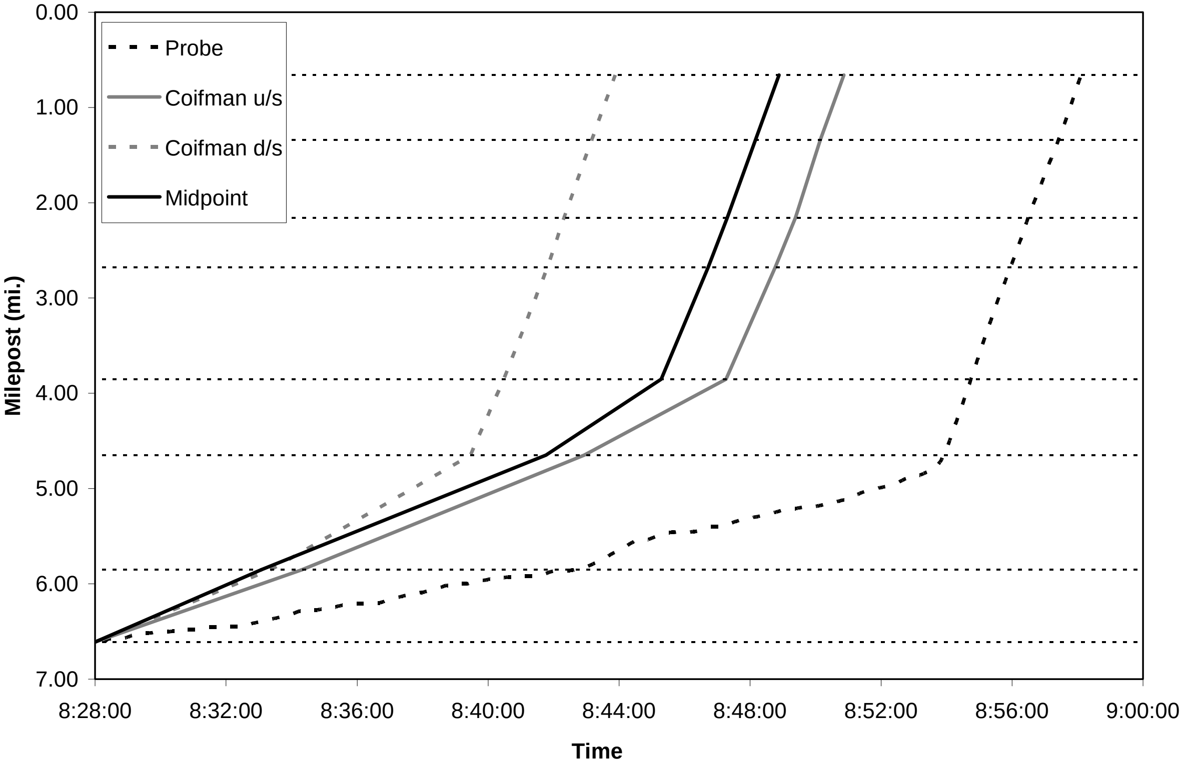


FIGURE 6 Probe, Coifman and midpoint trajectories during incident.

Detector Spacing

Probe vehicle, Coifman, and midpoint trajectories were also constructed for Link 6, which represents a section of I-5 just south of downtown. This part of the freeway is characterized by a nonstandard geometric feature known as the Terwilliger curves. In addition to the horizontal and vertical curves, the detector spacing is also large (~ 3 miles). Therefore, the trajectories were plotted in order to analyze the effect of detector spacing on the accuracy of travel time estimation and are shown in Figure 7.

Figure 7 displays the probe vehicle, Coifman (u/s and d/s) and midpoint trajectories in solid lines of varying colors and detector locations as dashed horizontal lines. From the graph, it is apparent that there is large spacing between the first and second detector locations. It has been observed that travelers slow down as they approach the curves and accelerate after passing the curves. Since there is no detector present at the exact location where deceleration and acceleration occur, the midpoint algorithm is not able to capture these effects, therefore resulting in a large error. The Coifman algorithm (u/s) produced the most accurate travel time estimate. From the above analysis, it follows that the midpoint travel time estimate is highly sensitive to large detector spacing.

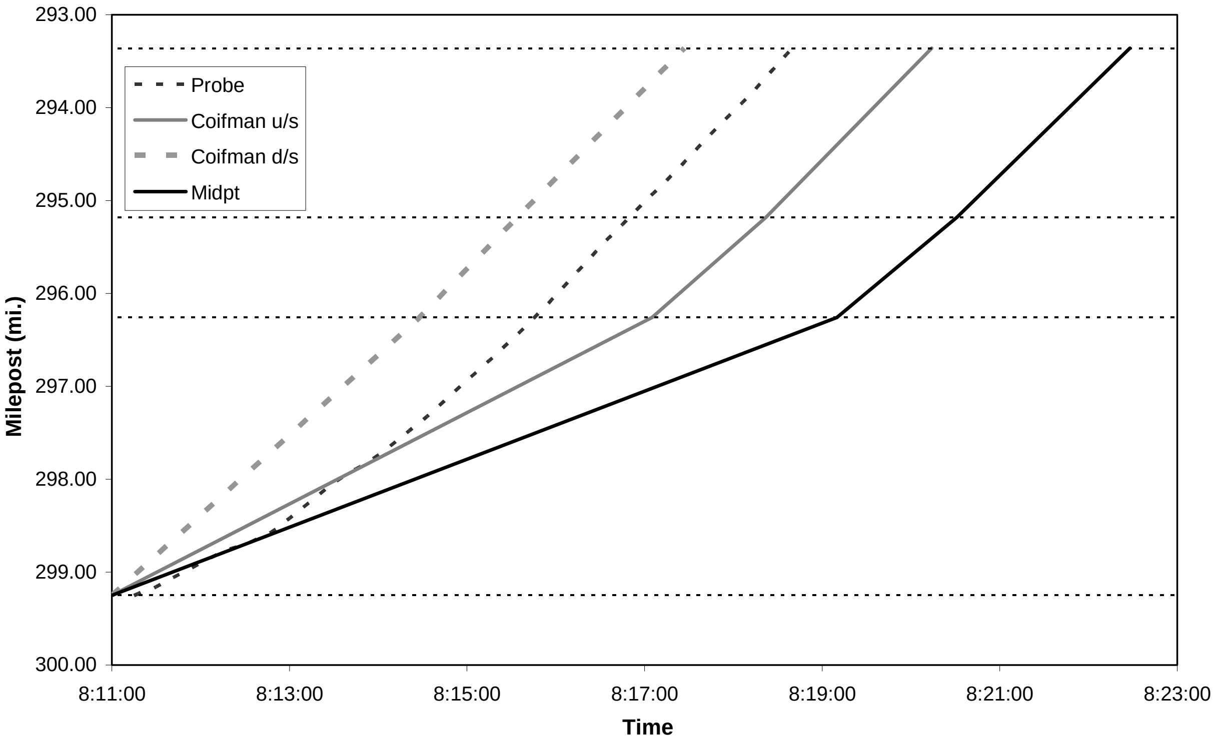


FIGURE 7 Probe, Coifman and midpoint trajectories for large detector spacing.

The above analysis indicates that all the algorithms generate accurate estimates when free flow conditions exist. The Coifman algorithm with the upstream detector speeds generates the most accurate travel time estimates during incidents and for links with large detector spacing. The midpoint algorithm generated travel times with larger error for links with incidents and large detector spacing. Therefore, the midpoint algorithm needs to be improved for such circumstances.

Tri-Met Bus Data Analysis

Travel time estimates were also generated using the six different methods described in the previous sections using the archived loop detector data from November 2002. These were compared to the Trimet bus travel times for route 96 which covered a section of I-5 N. Table 3 and Figure 4 show the mean travel times, standard deviations and the root mean square error for the bus, Coifman and Midpoint algorithms.

TABLE 3 Bus, Coifman, and Midpoint Travel Time Statistics

Day	Bus		Coifman (u/s)			Coifman (d/s)			Midpoint			Coifman-Midpoint			Coifman-Distwt		
	μ	*σ*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*	*μ*	*σ*	*RMSE*
Nov 5	5.57	0.98	5.41	0.41	0.68	6.36	0.87	0.92	5.80	0.63	0.70	5.85	0.58	0.62	5.75	0.54	0.59
Nov 6	6.85	2.02	6.53	1.26	1.08	7.99	1.99	1.37	7.11	1.85	0.94	7.29	1.64	0.87	6.98	1.41	0.88
Nov 7	8.93	6.15	9.46	6.45	1.34	9.79	5.45	2.41	10.58	9.71	5.24	9.63	5.86	1.75	8.86	4.83	1.73
Nov 12	12.34	4.66	10.91	4.75	2.24	12.65	3.66	1.57	13.92	9.11	5.68	11.74	3.89	1.62	10.95	3.65	2.12
Nov 13	12.93	6.35	14.13	7.47	2.66	12.68	5.29	1.78	12.61	6.53	4.22	13.47	6.56	1.78	12.46	5.71	1.89
Nov 14	8.12	3.01	7.16	1.73	2.77	8.71	2.73	3.28	7.72	2.87	3.11	7.88	2.15	2.89	7.38	1.74	2.86
Nov 19	5.43	0.75	5.57	0.50	0.45	6.32	1.05	0.87	6.13	1.41	0.71	6.01	0.86	0.59	5.84	0.71	0.44
Nov 20	8.62	3.35	7.28	1.80	2.14	8.71	2.66	1.15	7.68	2.72	2.08	8.08	2.27	1.47	7.53	1.85	2.03
Nov 21	9.43	3.46	8.54	3.39	1.99	9.73	3.19	1.02	9.62	4.28	2.31	9.29	3.41	1.35	8.61	2.81	1.59

Recognizing that the bus trajectories may be inherently slower than prevailing traffic speeds, the root mean square errors for all the algorithms compared in Table 3 indicate that the Coifman algorithm produces the least root mean square error for most cases. As indicated in the previous sections, the type of Coifman algorithm that produces the most accurate estimates depends on the location and formation of queue with respect to the detector station. Additional travel time estimates were also generated using the Coifman-midpoint method and the Coifman-distance weighting method. These travel time estimates are shown in Table 3.

CONCLUSIONS

The goal of this study was to analyze the performance of the standard ODOT midpoint algorithm along with different modifications of Coifman's algorithm. Travel time estimates produced using these algorithms were compared to ground truth travel times. The results indicate that all the algorithms generate accurate travel times during free flow conditions. While the Coifman algorithm implemented using the upstream detector speeds produced the best estimate during the period after an incident occurred, errors still exist in all estimates produced in the aftermath of an incident. Travel times were also analyzed for accuracy on links with large detector spacing. Again, the Coifman algorithm with the upstream detector speeds was found to produce the best travel time estimate. Based on the above analysis, the Coifman algorithm was found to be more accurate than the midpoint algorithm.

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