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Relieve Congestion and Conflicts Between Railroad and Light Rail Grade-Crossing Intersections

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Wei-Bin Zhang et. al

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Relieve Congestion and Conflicts Between Railroad and Light Rail Grade-Crossing Intersections

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University of California, Berkeley
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in collaboration with
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EXECUTIVE SUMMARY

This report specifically summarizes the work that the PATH team has performed at this stage of Task Order 6407 in continuation of previous Task Order 5407. We have conducted an in-depth study of problems associated with grade crossings for this project.

We started from the system design based on the proposed adaptive trolley signal priority (ATSP) system. The system is designed for large-scale field implementation of the ATSP system. It consists of three sub-systems: onboard sub-system, roadside control sub-system and central control sub-system. The system input and output diagram is based on the previous developed algorithm and programs.

We designed and conducted the laboratory testing for the ATSP system. The laboratory setting is the step prior to field operational testing of the proposed ATSP system in San Diego. The objective of the laboratory testing is to testify and demonstrate the applicability of the proposed system, particularly the communication system and the traffic signal operation system in San Diego, i.e. the QuicNet/4 central control system in the Transportation Management Center (TMC) and Type 170 controllers at roadside running McCain's Bitran 233 control software. There are two steps in the laboratory testing. The first step is to show the proposed system in an entirely closed laboratory environment. The second step is to move the testing one step closer to the FOT environment and involves field signal operation systems and the actual communication system.

The preliminary FOT was designed and conducted with the objective to demonstrate proof-of-concept of the proposed adaptive trolley signal priority (ATSP) in San Diego and to evaluate the potential applicability for such a system in a large-scale implementation.

Based on discussion with the City of San Diego and SANDAG, the testing site selected was the 0.8-mile-long arterial segment of C Street in Downtown San Diego. There are four trolley stations along this site. From the West side, they are America Plaza, Civic Center, 5th Ave., and City College. The site consists of fifteen signalized intersections from India St. to 10th Ave. Two trolley lines are serving this segment of C Street. They are the Blue and Orange Lines with regular service headway fifteen minutes. During the peak hour, the Blue Line runs higher frequent service with headway seven minutes.

There are two stages of data collection for the FOT. Stage one is for the "before" scenario in which trolleys do not experience any signal priority. Stage one is from October 30, 2009 to November 8, 2009. Stage two is the "after" scenario in which selected trolley trains are able to request transit signal priority along the testing corridor. Stage two started on October 16, 2009 and ended on October 26, 2009.

A thorough data analysis was conducted after the preliminary FOT. A successful trip was presented and analyzed. The proposed ATSP system was able to significantly reduce the

number of stops and stop times for the trolley trip. However, the overall performance of the proposed ATSP system was not as successful as expected. The maximum average reduction on average number of stops and average travel time is less than 15%. More issues were observed and studied from the perspective of trolley operation, traffic operation, and prediction for trolley movement and station dwelling time.

At the end of the report, all the issues were summarized. The project team also provides recommendations in order to further improve the system towards the next research step. The recommendations cover six aspects: signal transition, signal progression, dwelling time prediction, arrival time prediction at stations, integration of priority decision with prediction, and the automatic vehicle location (AVL) system. With all the system improvements and testing, the final FOT as the next step will be performed.

It is also noted that the proposed system design can be easily applied to other light-rail transit (LRT) systems, which do not have the preempted right-of-way at grade crossings and intersections. It is not necessary to have fixed-timing control at the signalized intersections. The proposed concept and system can be easily adapted to actuated or semi-actuated control systems. Moreover, the results and lessons learned from both of the laboratory test and the preliminary field operational test could help in designing and calibrating such transit signal priority systems for other similar LRT systems.

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1. System Design

As illustrated in Figure 1-1, the field-testing system consists of three sub-systems: onboard sub-system, roadside control sub-system and central control sub-system. PATH has developed a cost-effective solution for automatic vehicle location (AVL) systems, as shown in Figure 1-2. This system is based on Motorola iDEN phones with built-in GPS receivers and Java platform micro edition (J2ME). Although it is proved that the phone-based AVL system is sufficient to support adaptive transit signal priority along major arterials in the San Francisco Bay Area, it is still uncertain that such a system would be appropriate for the adaptive trolley priority system in downtown San Diego. As one of the objectives for the FOT, it is also to demonstrate the applicability of such cost-effective AVL systems to support ATSP in San Diego. On nine trolley trains, the cell phone-based system has been installed either on the roof of the operator's room or behind the destination sign window in front of the train depending on the power availabilities.

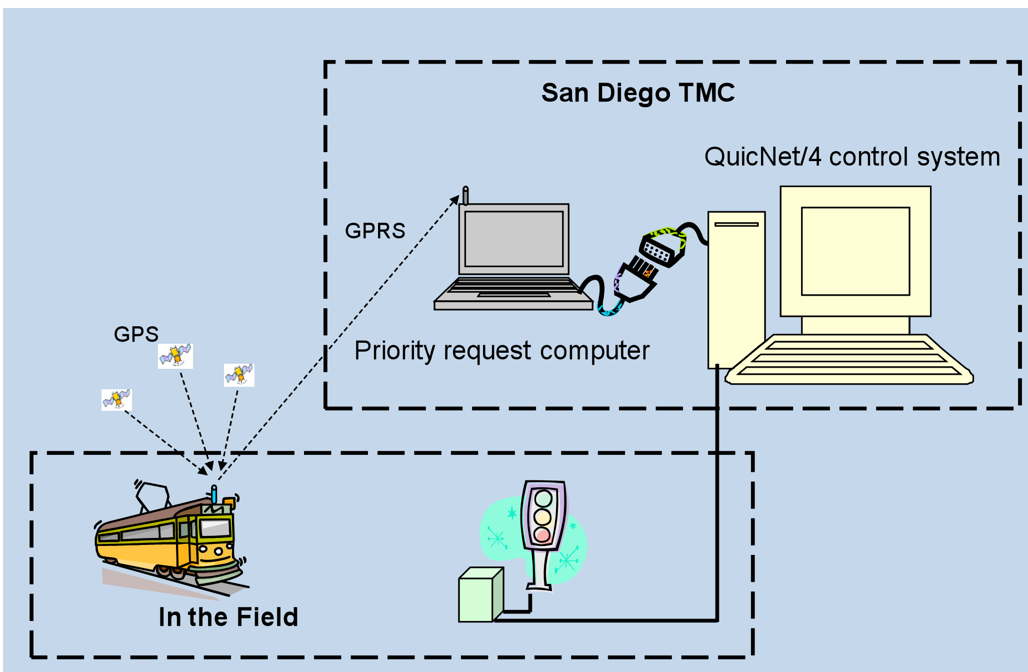

Figure 1-1 Physical architecture of San Diego ATSP System

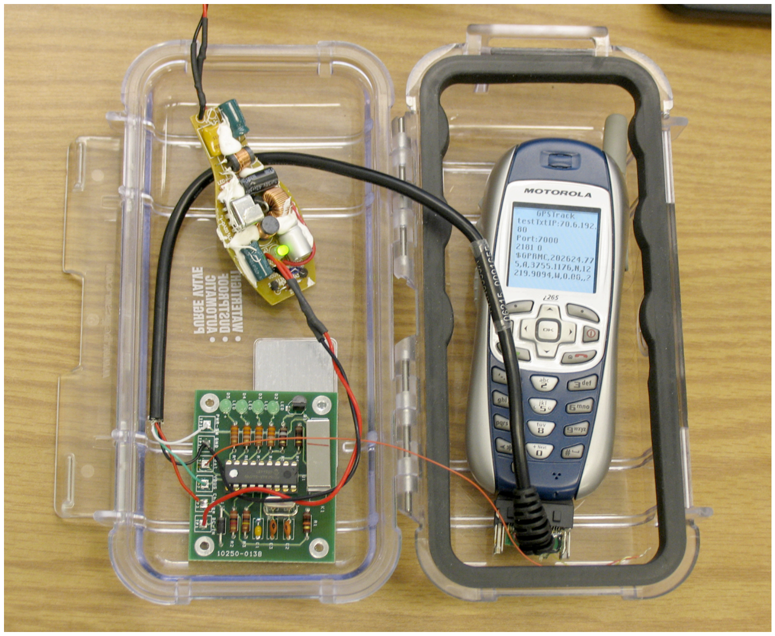

Figure 1-2 Cell Phone based AVL system

For the roadside sub-system, no additional equipment is installed in the controller cabinet for FOT testing. The existing two-way communication link between each local signal controller to the central traffic management center (TMC) has been examined before the FOT. In one direction, the signal controller is able to send detailed traffic operation information, e.g. current phase, running pattern, local clock timer, etc., in real time. In the opposite direction, the TMC can send priority requests with a set of proposed force-off points to the designated intersection. Once the request is received at the local signal controller, the signal timing would be changed before the next start of a signal cycle for the implementation of an ATSP request.

The central control sub-system consists of the QuicNet/4 server computer, the priority request generator computer, and the Ethernet communication link between them. The QuicNet/4 server manages communication between the central system and the local signal controllers in the field. Through the Ethernet communication link and an interface program jointly developed by McCain and PATH, the priority request generator computer receives the real-time traffic operation information from the local controllers in the field. Together with the real-time trolley location information from the AVL systems on trolleys, the offline optimization module is able to select the optimal force-off points for the intersections to provide priority to trolley trains when they arrive. Figure 1-3 illustrates the input and output diagram for the priority request generator. The optimization module runs in a Linux operating system and a data hub message queuing environment to support real-time operation.

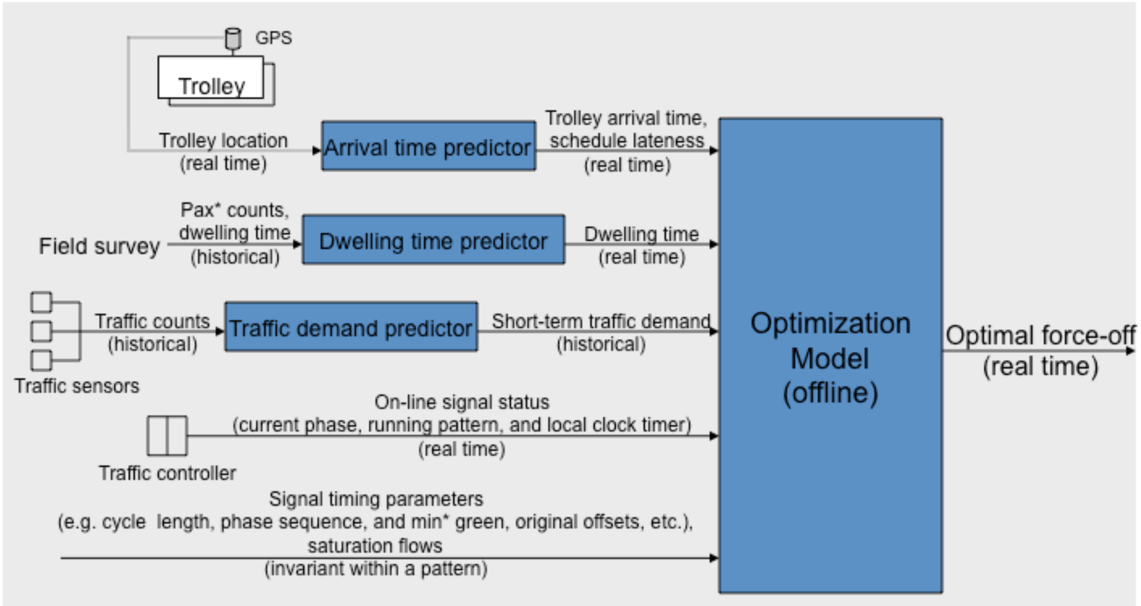

Figure 1-3 Input output diagram for the priority request generator

2. Laboratory Testing

2.1 Testing Purpose

The laboratory is the step prior to field operational testing of the proposed ATSP system in San Diego. The objective of the laboratory testing is to testify and demonstrate the applicability of the proposed system, particularly the communication system and the traffic signal operation system in San Diego, i.e. the QuicNet/4 central control system in the TMC and Type 170 controllers at roadside running McCain's Bitran 233 control software.

2.2 Testing Design

There are two steps in the laboratory testing. The first step is to show the proposed system in an entirely closed laboratory environment. The second step is to move the testing one step closer to the FOT and involves field signal operation systems and the actual communication system.

2.3 Laboratory Testing at PT^{2}L

McCain and PATH set up the testing environment at Parsons Traffic and Transit Laboratory (PT^{2}L) at PATH. The testing platform consists of three Type 170 signal controllers with McCain's Bitran 233 programs, a server computer with McCain's QuicNet/4 software installed, the communication links between the three signal controllers and the QuicNet/4 server computer, a PATH control computer with all the TSP software installed, and the communication link between the QuicNet/4 server and the PATH control computer. PATH then debugged and tested all the TSP software in this testing environment at PATH.

The original configurations of the signal controller setting in PATH's PT^{2}L are not identical with those at the San Diego Traffic Management Center (TMC). In particular, the "pre-timed" operation for phase 4 was enabled on the Bitrans 233 program. When McCain set up the controllers at PT^{2}L, the remote communication to SD's TMC had not been established yet. Thus McCain was not able to testify the settings with the field controllers. Under the incorrect settings at PT^{2}L, the force-off point of phase 4 is the time when the yellow of phase 4 starts. Under the field settings, phase 4 should be force-off at the beginning of its flash-don't-walk period. Under the help from the City of San Diego and McCain, such settings have been corrected. The control logic has been extensively examined. In addition, new constraints on force-off points of both phases as well as permissive end have also been tested in detail.

Because of the rectification of the signal controller settings, constraints of some parameters, e.g. force-off point of phase 4, or the relationship among parameters, e.g. the gap between force-off point of phase 2 and phase 4, were modified accordingly. According to the results, the feasible region of the proposed optimization model is a bit smaller than that without the modification.

In the lab testing, if there is no disturbance on the prediction departure/arrival time at stations/signals, then all trips for both directions will experience zero-stop along all intersections between stations. However, most situations in the real world are far from being ideal and the prediction results cannot be guaranteed to be perfect at all. Therefore, a sensitivity analysis on the prediction error is indispensable. The results are shown in Table 2-1 and Table 2-2.

Table 2-1 Sensitivity analysis for 3rd Ave and 4th Ave

	Sample Trips	*Delay at 3rd Ave*		*Delay at 4th Ave*	
		Mean	STD	Mean	STD
STD=0	29	0.17	0.38	0	0.00
STD=2	29	0.45	1.50	0.48	2.60
STD=5	28	6.89	16.92	5.11	15.18
STD=9	28	3.04	11.07	4.68	11.44
STD=14	27	5.48	10.79	13.59	17.09
STD=20	27	3.78	10.44	11.00	18.36

As can be observed from the results, system performance becomes worse as the standard deviation of the prediction error (unbiased prediction is assumed) gets larger. In other words, the overall delay of the simulated section, on average, keeps increasing. At the same time, the variation of such delay becomes more and more noticeable.

Table 2-2 Sensitivity analysis for 5th Ave and the section

	Sample Trips	*Delay at 5th Ave*		*Section Delay*	
		Mean	STD	Mean	STD
STD=0	29	0	0	0.17	0.38
STD=2	29	2.28	11.11	3.21	11.51
STD=5	28	0.25	0.80	12.25	21.00
STD=9	28	3.86	10.34	11.57	21.68
STD=14	27	4.45	12.39	23.52	21.32
STD=20	27	4.59	13.24	19.37	23.29

2.4 Laboratory Testing at San Diego TMC

PATH worked with the City of San Diego and McCain and set up the testing environment at the San Diego TMC. The testing platform was quite similar with the one at PATH. It consisted of five Type 170 signal controllers with McCain's Bitran 233 programs, the TMC QuicNet/4 server computer with McCain's communication software installed, the communication links between the five signal controllers and the QuicNet/4 server computer, a PATH control computer with all the TSP software installed, and the communication links between QuicNet/4 server and the PATH control computer and between the PATH control computer and the PATH server at PT^2L. PATH and the IT group at the City of San Diego set up a reverse connection so that the PATH control computer can receive the trolley GPS data from the PATH server computer in Berkeley. All the hardware and communication links were tested at the San Diego TMC. The five controllers were set up with identical settings as five field intersections at C Street: India Street, 3rd Avenue, 4th Avenue, 5th Avenue, and 6th Avenue.

Before using the trolley GPS data from the field to test our system, we first conducted the lab test with simulated trolley runs on the TMC testing platform. Under this scenario, our trolley simulation tool generated trolley trips and mimicked train movements. We set up the study corridor with 13 signalized intersections and sent out one trolley to travel back and forth. During the lab testing, five of the 13 traffic signals were controlled by real signal controllers as described above. The trolleys' historical movement data served as input parameters of our optimization model. In addition, the dwelling times at those four relevant stations, i.e. American Plaza, Civic Center, 5th Avenue and City College, came from both the historical operation data collected by the PATH automatic vehicle location (AVL) system and some latest field surveys conducted in June 2008. Starting from June 18th 2009, we have run the lab test in the San Diego TMC continuously for four days. With simulated trolley runs, we obtained over 500 trolley runs with equal number of trips for both Southbound/Outbound and Northbound/Inbound directions. Given the perfect prediction of train movements and dwell times, all trolley runs under signal priority were able to travel through signalized intersections without any unnecessary stops (i.e. non-station stops), except for those trips released at around midnight. The cause of the stops was due to abnormal controller operation, which will be described in detail in a later section. To analyze the simulation data, we developed our tools using MATLAB to visualize the results and get further insight of the trolley and signal operations. Figure 2-1 shows one typical Southbound/Outbound trip in the lab test. After detecting the incoming trolley, the PATH control computer generated signal priority requests based on the movement of trolley trains and signal timings from the QuicNet/4 server, which then downloaded the signal timings onto the three controllers that were set up in the TMC. After the controllers implemented the new timings, the simulated trolley with priority was able to go through all three intersections without any stops. Note that the dwell times have been equivalently converted to travel times.

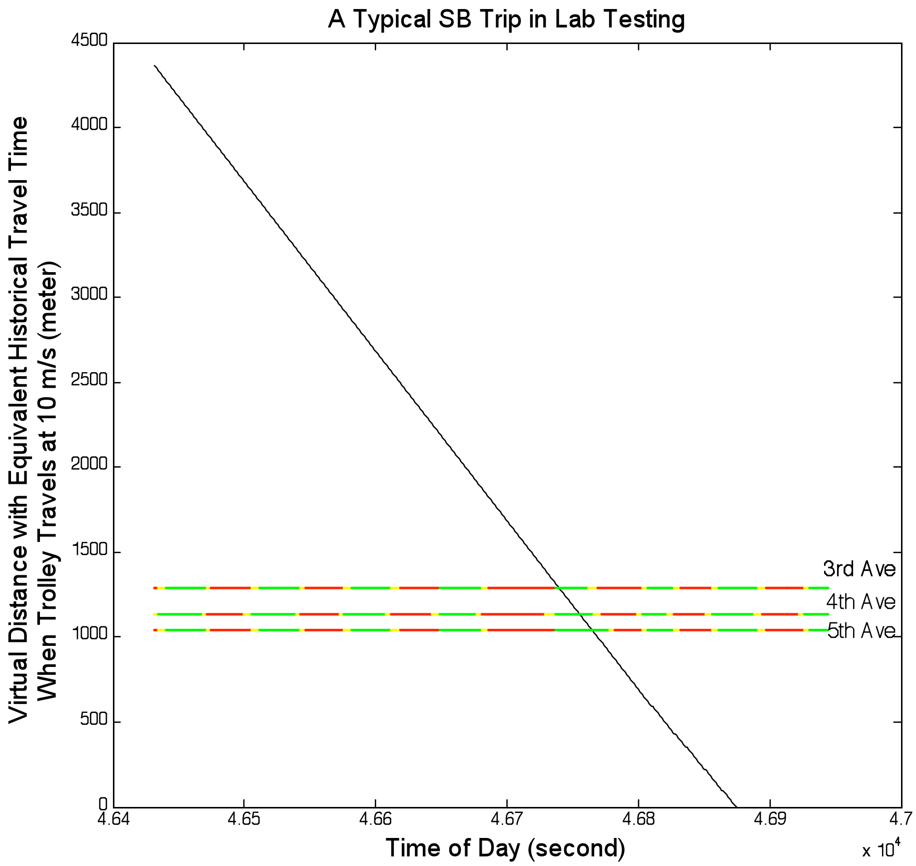

Figure 2-1 One typical southbound/outbound laboratory testing trip

Based on our observations and discussions with City of San Diego engineers, we learned that all signal controllers along the study corridor are reset at approximately midnight (00:00 A.M.) each day. During this time, all signal controllers are in transition for at least 150 seconds. This caused the trolley request to be dropped or not properly implemented. As a tentative solution, we can block out a 10-minute period around midnight when we would not process any signal priority requests.

Although our prediction tool is trying to filter out the GPS-related error, the worst of GPS receptions will result in the worst of prediction outputs. Subsequently, the traffic signal timings can hardly be adjusted to adapt to the trolleys' field movements. As mentioned before, there are two types of GPS problems: GPS reception error and GPS signal loss. Both of these errors are partially due to "urban canyon" effects and the limitation of our GPS devices. According to the test results, the quality of GPS data is adequate for the field test with the purpose of verifying our ATSP system. For the field deployment of the system, a more robust device will be needed.

The prediction of train dwell time is very difficult particularly with the random arrivals of disabled people. However, this quantity is also a key parameter to our system because signal controllers in pre-time mode require long lead-time to process timing change requests. Based on extensive tests in the simulation environment, our algorithm will definitely work well if the prediction is good enough. In comparison with trolleys' travel time, dwell time is less consistent and more unpredictable. For example, if there is a handicapped person who needs to board the train, the dwell time will get much longer than usual. According to the field data analysis, trolleys' waiting times (may include dwell time and signal waiting time) at the station can range from approximately 30 seconds to 3 minutes. One possible way to increase the accuracy of the dwell time prediction is to build learning intelligence in the prediction software so that the prediction tool can improve itself by learning from the collected field data.

3. Preliminary Field Operational Test

3.1 Testing Purpose

The objective of the preliminary field operational test (FOT) was to demonstrate proof-of-concept for the proposed adaptive trolley signal priority (ATSP) in San Diego and evaluate the potential applicability for such a system in a large-scale implementation.

3.2 Testing Description

Based on discussions with the City of San Diego and SANDAG, the selected testing site was the 0.8-mile-long arterial segment of C Street in Downtown San Diego, as shown in Figure 3-1 with four trolley stations along this site: From the west to east, they are America Plaza, Civic Center, 5th Ave., and City College. The site consists of fifteen signalized intersections from India St. to 10th Ave. and two trolley lines serve this segment of C Street. They are the Blue and Orange Lines with regular service headway of fifteen minutes. During the peak hour, the Blue Line runs more frequent service with seven-minute headways.

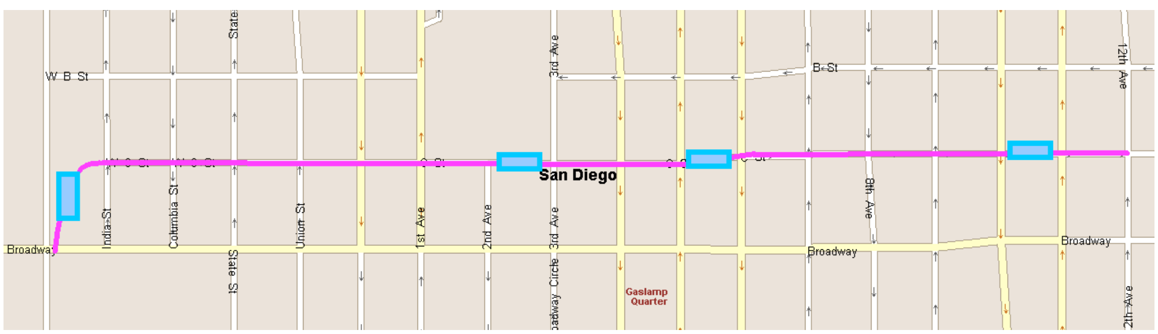

Figure 3-1 Map of testing Site

There were two stages of data collection for the FOT. Stage one was for the "before" scenario in which trolleys did not experience any signal priority. Stage one was from October 30, 2009 to November 8, 2009. Stage two was "after" scenario in which selected trolley trains were able to request transit signal priority along the testing corridor. Stage two started on October 16, 2009 and ended on October 26, 2009. Table 3-1 presents the summary of sample trips in the FOT. Table 5-1 in the Appendix and Table 3-2 illustrate the detailed description of all the trip samples for Stage 1 and Stage 2, respectively.

Table 3-1 Summary of trip samples

Stage	*Number of trips*	
	Outbound	Inbound
1 (No TSP)	67	79
2 (With TSP)	109	123

Table 3-2 Detailed trip samples for Stage 2

Date (Oct.)	*Trolley #1*		*Trolley #2*		*Trolley #6*		*Trolley #8*		*Summary*	
	OB*	IB**	OB	IB	OB	IB	OB	IB	OB	IB
16th	0	0	5	5	1	2	3	3	9	10
17th	0	0	8	8	0	0	3	3	11	11
18th	0	0	0	0	0	0	5	4	5	4
19th	0	0	8	9	2	2	8	9	18	20
20th	0	0	7	8	2	2	1	1	10	11
21st	1	1	4	5	1	2	5	6	11	14
22nd	8	9	5	7	2	4	3	2	18	22
23rd	9	9	8	9	3	3	6	7	26	28
24th	7	7	2	1	0	0	3	3	12	11
25th	8	8	0	0	0	0	0	0	8	8
Sum.	33	34	47	52	11	15	37	38	128	139

* – Outbound trips include those operating along both Blue and Orange Lines within the study scope

** – Inbound trips include those operating along both Blue and Orange Lines within the study scope

The traffic signal timings serve as major inputs of the proposed optimization model. Since last time PATH did the data collection, San Diego city engineers have updated signal timings a few times. In order to prepare for the FOT, the most recent signal timing sheets have been collected from the City of San Diego. All timing parameters in our control software have been updated. In comparison with the previous version of traffic signal timings, the changes include offsets, force-off points of phase 4, yellow intervals and all red clearances.

Due to the construction project around San Diego City College, the City College trolley station was placed between 10th and 11th Avenues at C Street. Therefore, the original study corridor was from India Avenue @ C Street to 10th Avenue @ C Street. The whole corridor consisted of 12 signalized intersections. Upon the completion of the construction project, the City College station was relocated between 11th Avenue @ C Street and Park Boulevard @ C Street. Now there are 13 signalized intersections along the study corridor: India Street, Front Street, 1st Avenue, 2nd Avenue, 3rd Avenue, 4th Avenue, 5th Avenue, 6th Avenue, 7th Avenue, 8th Avenue, 9th Avenue, 10th Avenue and 11th Avenue. For the additional intersection 11th Avenue @ C Street, we have collected and analyzed the traffic signal timing information, geometry information, and traffic demand information. 11th Avenue @ C Street is quite unique from a geometric perspective because it has a separate traffic phase, which parallels the trolley direction of movement. Therefore, we made a few changes in our signal timing optimization software and generated the prioritized signal timings.

In our previous work, we focused on signal timing Plan 2 for our study corridor. Plan 2 covers the time of day between 03:00 and 15:00. It is also consistent with the study period that we set in the microscopic simulation model using PARAMICS. However, the trolley operational span is longer than the time window mentioned above. The optimal timing tables under Plan 4 are thus required and have been obtained by running the proposed optimization model.

3.3 Results Analysis

3.3.1 System Performance

A successful implementation of the ATSP system depends on whether a priority request can be properly generated, then communicated and finally deployed. Table 3-3 presents the execution rates for the priority requests at all the intersections along the test site. It is observed that the majority of priority requests have been successfully executed. At most signals, over 98% of requests can be successfully generated, communicated, and executed at local signal controllers. At 11th Ave, there were five failure calls, which is 6% of all requests. According to the communication log file, communication issues between the QuicNet/4 server and the local signal controller likely caused the non-executions, e.g. at 11th Ave.

Table 3-3 Summary of execution rates for requests

Intersection	*Total Number of Requests*	*Updated Calls*	*Effective Calls*	*Successful Calls*	*Failure Calls*	*Successful Rate*
India St	175	70	105	103	2	98%
Front St	181	85	96	96	0	100%
1st Ave	179	79	100	100	0	100%
2nd Ave	178	82	96	96	0	100%
3rd Ave	148	62	86	86	0	100%
4th Ave	145	53	92	91	1	99%
5th Ave	154	63	91	90	1	99%
6th Ave	149	60	89	89	0	100%
7th Ave	148	61	87	87	0	100%
8th Ave	145	59	86	86	0	100%
9th Ave	152	58	94	93	1	99%
10th Ave	143	56	87	87	0	100%
11th Ave	141	56	85	80	5	94%

3.3.1.1 Impacts on Trolley Operation

For part of the proof-of-concept for the proposed methodology, a real-world example trip was taken to evaluate system performance. Figure 3-2 shows the trajectory of the example trip from the Civic Center Station to the 5th Ave Station. As is illustrated in the figure, there is no stop on red along the three signalized intersections of 3rd Ave, 4th Ave and 5th Ave between two stations, due to the successful execution of the priority request.

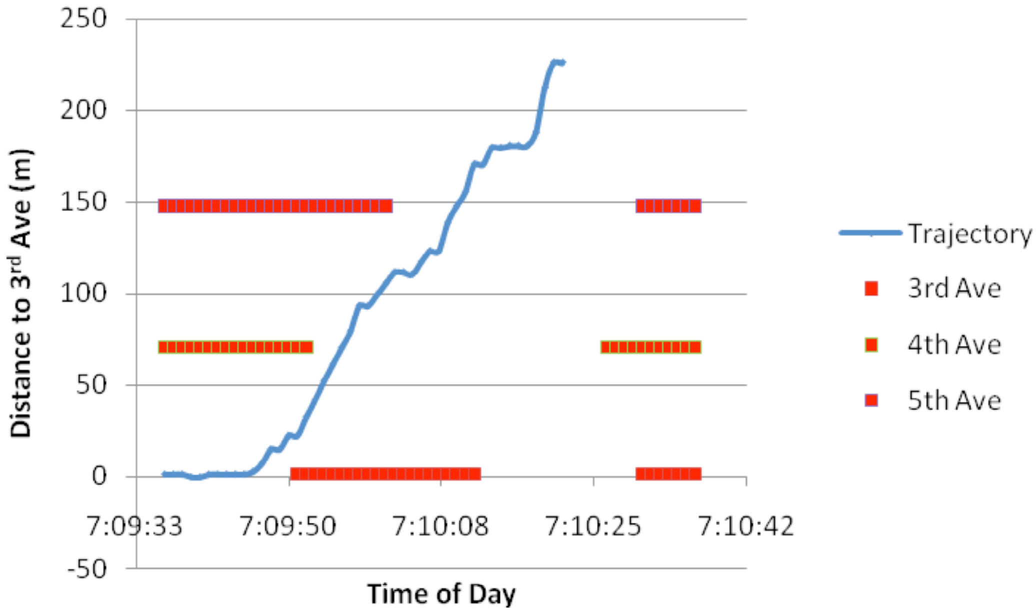

Figure 3-2 Trajectory of an example trip from Civic Center to 5th Ave

By carefully examining this trip, it can be observed that the actual departure time from the Civic Center Station is 07:09:46 a.m., while the predicted departure time is 07:09:43 (only 3 seconds earlier). Based on such a good prediction, a priority request on the changes of signal timings is generated and executed. As a result, the differences between actual departure times and predicted times are trivial for the other two downstream intersections, i.e. 4th Ave and 5th Ave. The performance of this example trip is illustrated in

Table 3-4.

To further evaluate the benefit obtained from the proposed methodology, a hypothetical trip under original signal timings was constructed and its performance was compared with the scenario under the proposed signal timings. More than 16 seconds can be saved for this example trip at 3rd Ave (see Table 3-6). More specifically,

a) If no priority request is available, the trolley will face the second half of red at 3rd Ave. However, this trolley passed through all three signals without any stop due to the successful execution of signal priority requests;
b) A dedicated 'green band' (not too wide) along the trolley's direction guaranteed such non-stop movement;
c) At the same time, a wide 'green band' in the other direction made sure that the priority execution would not affect the trolleys' movements from the opposite direction.

Table 3-4 Performance of an example trip from Civic Center to 5th Ave

	3rd Ave	*4th Ave*	*5th Ave*
Pred. Leave Time	07:09:43	07:09:59	07:10:08
Act. Leave Time	07:09:46	07:09:57	07:10:09
Pred. Error (sec)	-3	2	-1
Block Travel Time (sec)	11		12

Table 3-6 Original and proposed timings for the example trip

	3rd Ave		*4th Ave*		*5th Ave*	
	FO 2 *	FO 4 **	FO 2	FO 4	FO 2	FO 4
Before Timings	0	34	0	34	0	34
After Timings	23	52	0	32	0	37
Expected Delay (sec)	>=16		0		0	

However, not all trips with priority request execution gain such satisfactory results and not all results under proposed signal timings are consistently better than those in the original scenario. The summary of all trips is presented below.

As is shown in

Table 3-7, TSP successfully reduced by about 10% the number of stops along Section I (between the American Plaza Station and the Civic Center Station). The standard deviations are comparable for the same section. Insignificant benefits can be obtained with applications of ATSP methodology for Section II, while minor negative impacts on the number of stops along Section III are present. In the opposite direction, the results are similar. TSP reduced by about 10% along Section I and reduced another 15% along Section II. Along Section III, TSP was unable to significantly benefit trolley operation.

Table 3-7 Summary of number of stops at signals

Stage	*Section I*		*Section II*		*Section III*	
Inbound trips	Mean	STD	Mean	STD	Mean	STD
1 (No TSP)	1.78	0.82	0.83	0.63	1.00	0.79
2 (with TSP)	1.61	0.81	0.83	0.64	1.33	0.96
Outbound trips	Mean	STD	Mean	STD	Mean	STD
1 (No TSP)	1.29	0.86	0.95	0.61	2.38	0.78
2 (with TSP)	1.19	0.88	0.79	0.61	2.38	0.79

The impact of TSP on trolley travel time is similar with that on the number of stops as shown in

Table 3-7. The benefits were insignificant for most of trips due to some external and internal issues, among which, the inaccurate prediction of train departure time is one of the most important. The further detailed analysis is in the following section.

At stage 2 with TSP, some of the priority requests may be blocked due to an earlier priority request execution for the other trolleys. To quantify the percentage of priority requests not blocked, a priority request 'non-blockage' rate, δ, is defined at a section level (a section is defined as the segment between two consecutive stations).

For Section i, 'non-blockage' rate of priority requests is

$$\delta_i = \#\ of\ trips\ with\ executed\ priority\ requests\ /\ \#\ of\ trips$$

Table 3-9 presents the results of this rate for different trip directions (outbound and inbound). As is shown in the figure, the ATSP request ‘non-blockage’ rate is greater than 0.9 in most cases, which means that over 90% priority requests can be executed within the scale of the field operation test. With the larger scale deployment, a higher request blockage rate may be expected. However, based on schedule adherence, if only those late trolleys (around 10% of overall trips) sent out the priority request, the ATSP request blockage rate should also fall into an acceptable range.

Table 3-9 Request non-blockage rates

Section	*Trolley #1*		*Trolley #2*		*Trolley #6*		*Trolley #8*	
	OB	IB	OB	IB	OB	IB	OB	IB
Sec. I	0.92	1.00	0.91	0.96	0.88	1.00	0.95	1.00
Sec. II	1.00	1.00	0.98	1.00	1.00	1.00	0.95	1.00
Sec. III	0.96	0.81	0.98	0.92	1.00	0.92	1.00	0.92

A priority request consists of a set of force-off points for the intersections between downstream and upstream trolley stations. With the changes of force-off points, the starts, ends, and durations of signal phases would all change. When under priority, signal phase 2 serving the trolley movement direction would be relocated to cover the trolley's arrival time and elongated to cover the deviations of the trolley's arrival.

Table 3-11 summarizes the impacts on signal cycles for the "after" scenario. Among the total of 1234 cycles, the number of effective calls at different intersections varies due to the blockage effects and correction calls with updates on arrival predictions. Given the current FOT setup with limited trains under priority, the percentage of impacted cycles is low, which is around 7%. It is noted that the transit priority should be conditioned, e.g. by schedule adherence, if traffic operators or city engineers would like to set an upper bound percentage of impacted cycles in order to limit the total impacts on traffic signal coordination.

Table 3-11 Summary of impacts on signal cycles

	Total Number of Cycles	*Effective Calls*	*Percentage of impacted cycles*
India St	1234	105	8.5%
Front St	1234	96	7.8%
1st Ave	1234	100	8.1%
2nd Ave	1234	96	7.8%
3rd Ave	1234	86	7.0%
4th Ave	1234	92	7.5%
5th Ave	1234	91	7.4%
6th Ave	1234	89	7.2%
7th Ave	1234	87	7.0%
8th Ave	1234	86	7.0%
9th Ave	1234	94	7.6%
10th Ave	1234	87	7.0%
11th Ave	1234	85	6.9%

Table 3-13 summarizes the changes in durations and force-off points in phase 2 that serve the trolleys' direction. For all the intersections, the average changes on phase 2 durations are positive because the proposed ATSP system tries to minimize the expected trolley delay given that the trolleys' arrivals are random. Both of the changes in durations and in percentages varied among intersections. The maximum average change is about 12 seconds at 9th Ave, while the largest percentage of change is about 35% at 8th Ave, as shown in Figure 3-3. Although the changes within the two priority cycles are around 7 seconds and 20%, which is not low, the changes over a whole day considering the total number impacted cycles are still very low, which are around 2%, e.g. 2.5% at India Street as shown in Figure 3-4. The results for other intersections can be found in the Appendix.

Table 3-13 Summary of changes on phase 2 (trolley phase)

	Phase 2 Duration				*Phase 2 Force-Off (FO)*		
	Original duration (sec)	Average change by priority (sec)	Change for priority cycles (%)	Change over a day (%)	Original FO	Average change by priority (sec)	Change over a day (sec)
India St	37	10.87	29.4%	2.50%	0	17.1	1.45
Front St	31	7.82	25.2%	1.96%	0	10.6	0.83
1st Ave	30	4.57	15.2%	1.24%	0	12.0	0.97
2nd Ave	31	8.23	26.5%	2.06%	0	13.2	1.02
3rd Ave	32	5.32	16.6%	1.16%	0	10.4	0.72
4th Ave	32	4.70	14.7%	1.10%	0	14.5	1.08
5th Ave	32	5.99	18.7%	1.38%	0	17.9	1.32
6th Ave	32	6.08	19.0%	1.37%	0	17.3	1.25
7th Ave	32	6.32	19.7%	1.39%	0	11.4	0.80
8th Ave	24	8.44	35.2%	2.45%	0	9.7	0.68
9th Ave	37	11.97	32.3%	2.46%	0	14.3	1.09
10th Ave	33	5.82	17.6%	1.24%	0	8.8	0.62
11th Ave	28	6.90	24.6%	1.70%	0	15.3	1.05

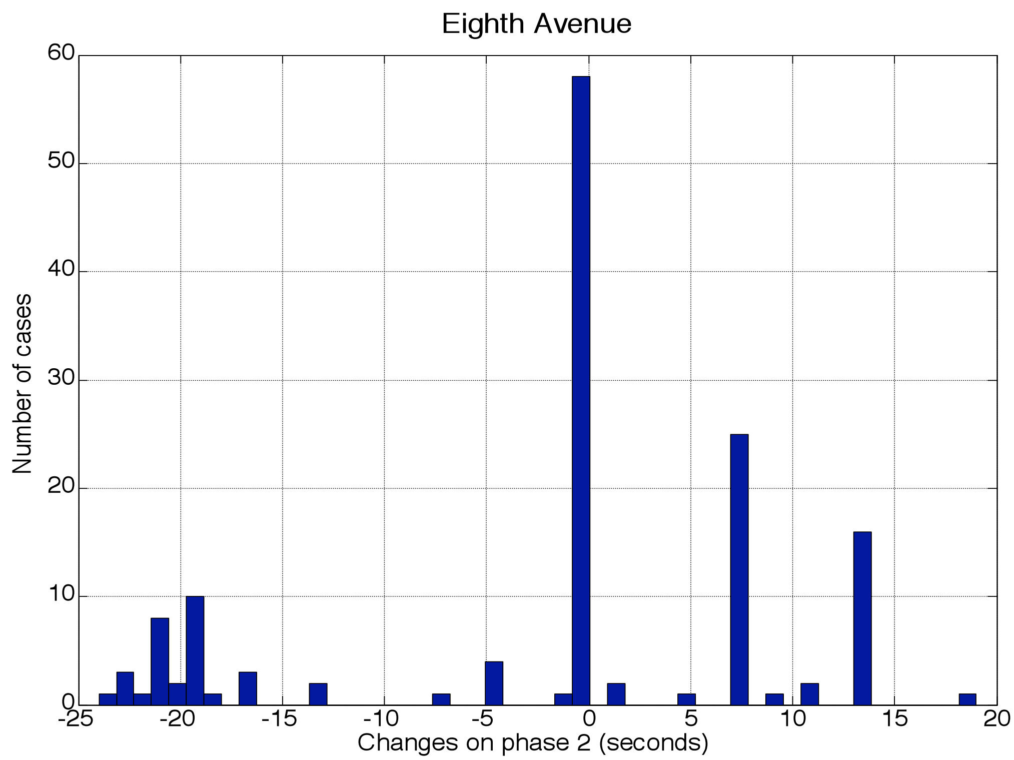

Figure 3-3 Changes on phase 2 at 8th Ave

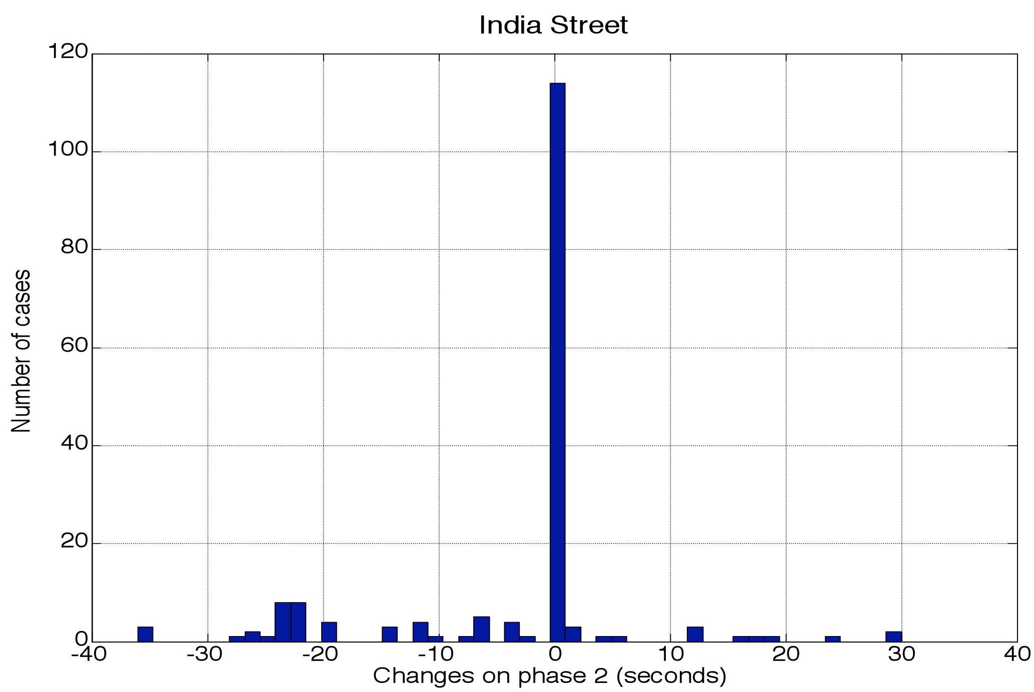

Figure 3-4 Changes on phase 2 at India Street

The changes on force-off points of phase 2 reflect how much priority requests shift from the original timings. As illustrated by Table 3-13, the average changes by priority are approximately14 seconds compared with the original force-off point for phase 2 at the beginning of the local clock. The changes during the priority cycles are significant in order to substantively reduce trolleys' delay. However, the changes over a day considering the total number of impacted signal cycles are negligible and only 1.7%.

3.3.1.2 Impacts on Traffic Operation

The major concern for transit signal priority is the impact on general traffic. Traffic engineers from the City of San Diego worry about the incurred delay and number of stops for general traffic by providing transit signal priority at busy C Street. Table 3-15 summaries the changes on phase 4 for general traffic. Among all the intersections, the average change in duration of phase 4 is 4.9 seconds. The largest average change is 7.1 seconds at India Street, as shown in Figure 3-5. Although the average change in duration of phase 4 is around 20% that is significant within the two priority cycles, the impacts over a whole day considering the number of impacted cycles per day is only 1.3%, which is negligible. The distribution of signal changes on phase 4 at other intersections can be found in the Appendix.

Table 3-15 also presents the changes in phase 4 force-off points, which are an indicator of how much the priority requests shift the signal timings from the original signal coordination. Across all the testing intersections, the average change of phase 4 force-off points is 6.7 seconds. The maximum average change is 9.35 seconds at India Street. Although the change is significant over the two priority cycles, the average change over a whole day is only 0.5 second, which is very small and negligible. According to the testing log files, trolleys with extensive long dwell time generated multiple requests. With more strict constraints on the number of requests for one trolley trip, the impact on other traffic can be further reduced.

Table 3-15 Summary of changes on phase 4 (general traffic)

	Phase 4 Duration				*Phase 4 Force-Off (FO)*		
	Original duration (sec)	Average change by priority (sec)	Change for priority cycles (%)	Change over a day (%)	Original FO	Average change by priority (sec)	Change over a day (sec)
India St	18	7.10	39.5%	3.36%	34	9.35	0.80
Front St	30	5.01	16.7%	1.30%	35	7.18	0.56
1st Ave	31	3.27	10.6%	0.86%	36	5.45	0.44
2nd Ave	30	5.54	18.5%	1.44%	35	6.50	0.51
3rd Ave	29	3.16	10.9%	0.76%	34	4.78	0.33
4th Ave	29	3.10	10.7%	0.80%	34	5.62	0.42

5th Ave	29	4.76	16.4%	1.21%	34	6.82	0.50
6th Ave	29	4.67	16.1%	1.16%	34	6.52	0.47
7th Ave	29	4.31	14.9%	1.05%	34	9.16	0.65
8th Ave	37	6.31	17.1%	1.19%	42	6.08	0.42
9th Ave	24	7.03	29.3%	2.23%	29	8.37	0.64
10th Ave	28	3.97	14.2%	1.00%	33	5.10	0.36
11th Ave	33	5.22	15.8%	1.09%	34	6.03	0.42

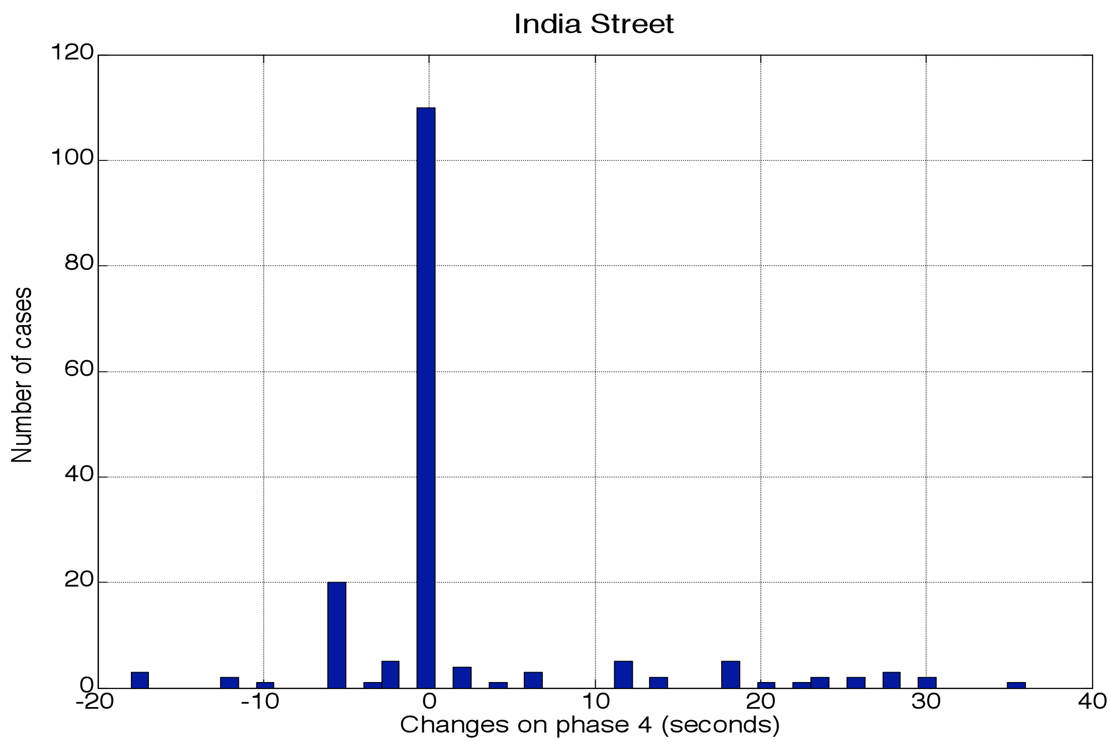

Figure 3-5 Changes on phase 4 at India Street

3.3.2 Prediction Analysis

The current algorithm was initially built for 'short-term' (i.e. nearest signal) prediction. It aimed for applications with the capability of making instant changes on force-off points. A dynamic predicted arrival time to the nearest signal is calculated by combining both current trolley speed and historic trolley travel time. The predicted arrival time to the prioritized signal is the sum of the dynamic predicted arrival time to the nearest signal, the average 'historic' non-stop travel time between the nearest signal and the prioritized signal, and the dwell time at stations in between. It is noted that the trolley is assumed to travel continuously between consecutive signals when no stations are in place.

3.3.2.1 GPS Reception

In the FOT, the cell phone-based AVL systems (Figure 1-2) were installed on selected trolley trains. Such systems failed to function as expected as shown in Figure 3-6 where both of the two outbound Orange Line trips deviate substantially from the tracks, particularly at the two corners of C Street, where America Plaza Station and City College Station are located. Figure 3-7 illustrates two Blue Line trajectories with similar and consistent reception issues.

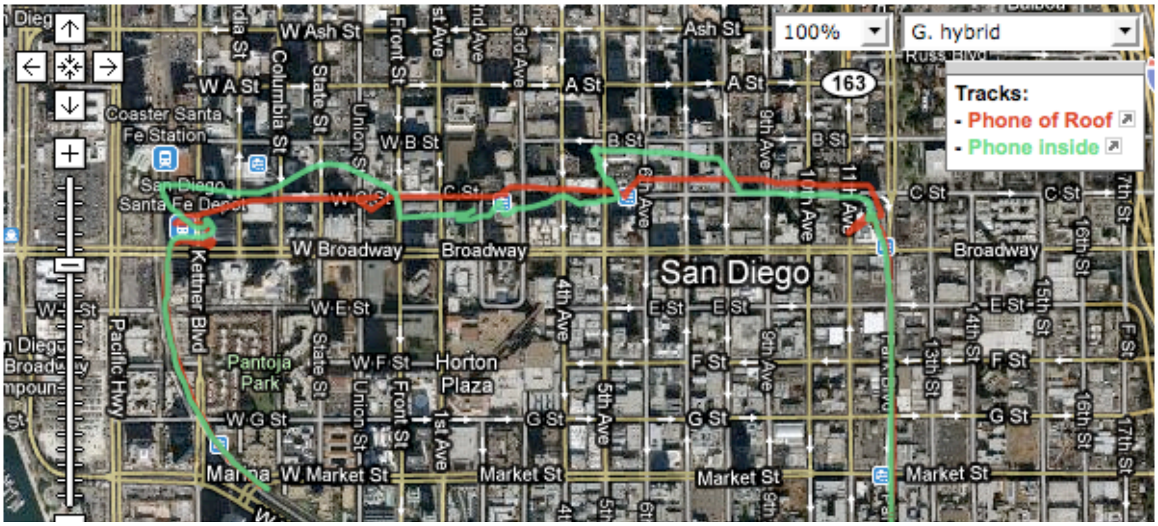

Figure 3-6 GPS trajectories for two Orange Line trips

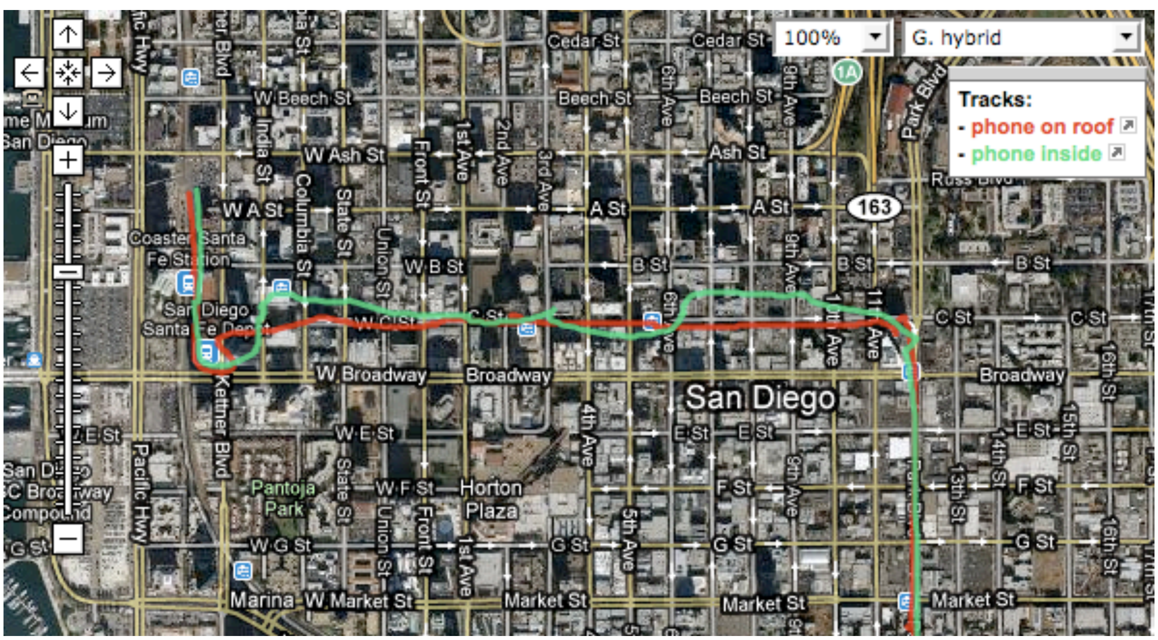

Figure 3-7 GPS trajectories for two Blue Line trips

The bad receptions are mainly due to two reasons. First, the cell phone-based AVL system does not have an external antenna for the GPS receiver and limits the capabilities of the device to obtain good satellite information. Second, the GPS receivers at the testing site in downtown San Diego experience the so-called "urban canyon" effect. An urban canyon is an artifact of an urban environment similar to a natural canyon. It is manifested by streets cutting through dense blocks of structures, especially skyscrapers. Urban canyons have an impact on radio reception, particularly reception of GPS signals. Moreover, the tracks around America Plaza Station have a glass roof, which also significantly impacts GPS reception.

3.3.2.2 Motion Prediction

Figure 3-8 shows a typical trolley trip (inbound trip for Figure 1). As shown in the figure, the trolley usually stops for a long time between the predicted starting point and the 1st test signal. This observation is quite different from the assumptions of prediction. As shown in the figure, the first test signal for the inbound trip is C St at 11th Ave (signal C13). The inbound trolley first stopped at Park & Market Station for about 45 seconds and then stopped at first station (City College) for 87 seconds. Such discrepancies between reality and assumption create large prediction errors for the predicted arrival times at the first test signal and start a "chain reaction" along downstream signals. For example, the trolley also stopped before signal C12 (C St at 10th Ave), which is the downstream signal of signal C13 due to a large prediction error of arrival time at signal C12.

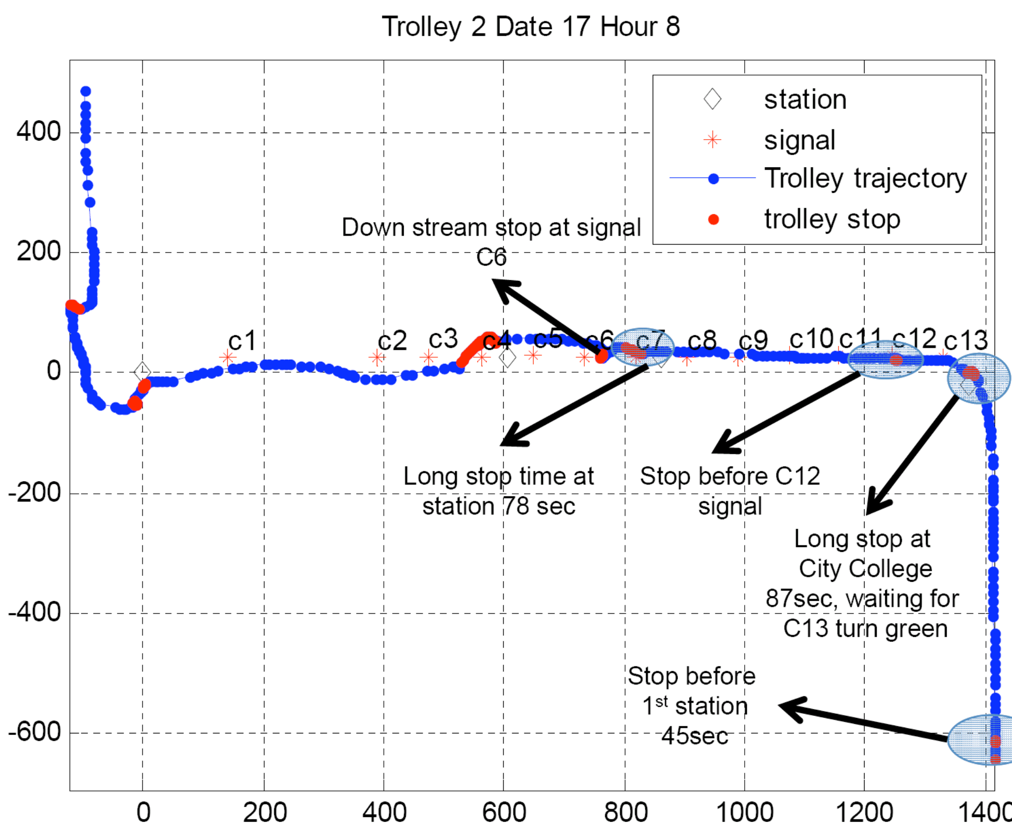

Figure 3-8 A typical trolley trajectory

Figure 3-9 and Figure 3-10 show the histogram of prediction error. When the assumption of prediction is met, i.e. no stop in between stations, the prediction is very accurate. Otherwise large prediction errors dominate.

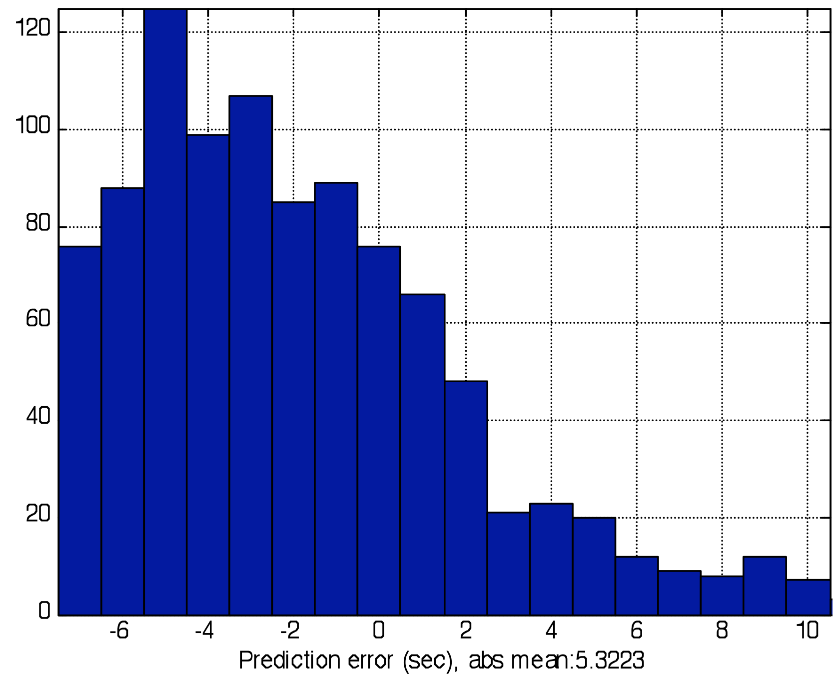

Figure 3-9 Distribution of prediction errors without stopping time at stations

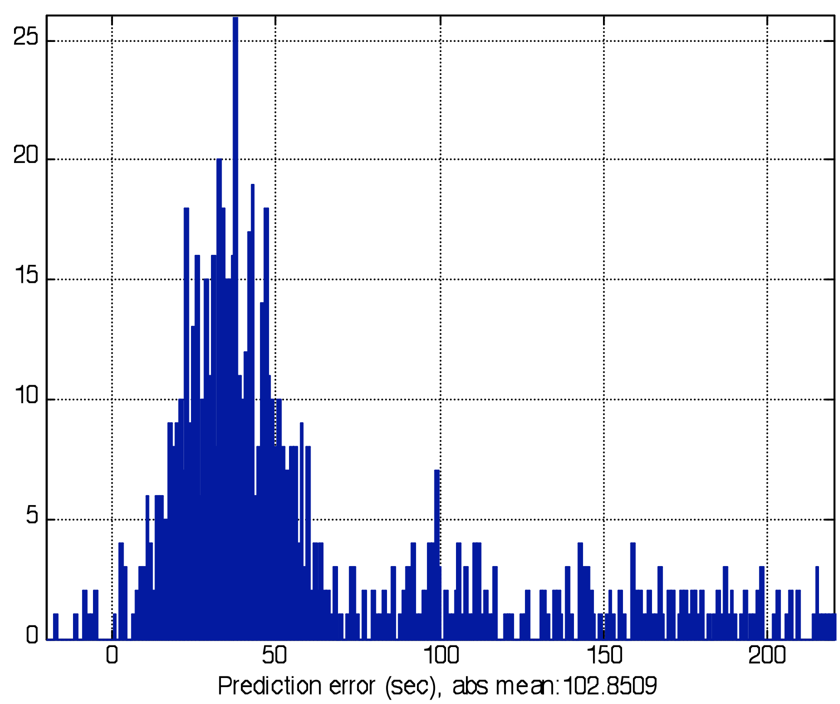

Figure 3-10 Distribution of prediction errors with stopping time at stations

3.3.2.3 Dwelling Prediction

The prediction of train dwell time is very challenging. Because all the trolley stations in downtown San Diego are near-side stations, the total trolley dwell time is the sum of passenger loading time, door open/close time, and signal waiting time. As discussed in an earlier report under Task Order 5407, the passenger loading time is highly random because of unpredictable passenger arrivals and passenger activities. In spite of fixed-timing control, the signal waiting time at stations is also random because train arrivals plus passenger loading time is random.

Some observations can be made together with conclusions from the data analysis. The distribution of dwell times at trolley stations do not have time-of-day patterns, as shown in Figure 3-11 and Figure 3-12 for America Plaza Station and 5th Avenue Station, respectively. Distribution of dwell time at some stations shows "dual-layer" phenomena, as shown in Figure 3-12. The average time difference of the two "layers" is around 70 seconds, which is exactly a full signal cycle. Such phenomenon shows that the trolley arrival times at the 5th Avenue Station normally situate at a similar location on the local signal control clock for the downstream intersection. The departure time would be either the next start of green or the following green if the trolley cannot finish loading passengers by the beginning of green. Operators actually follow the rule of departing stations only at a fresh green. It is noted that such phenomenon normally happens when TSP is not activated.

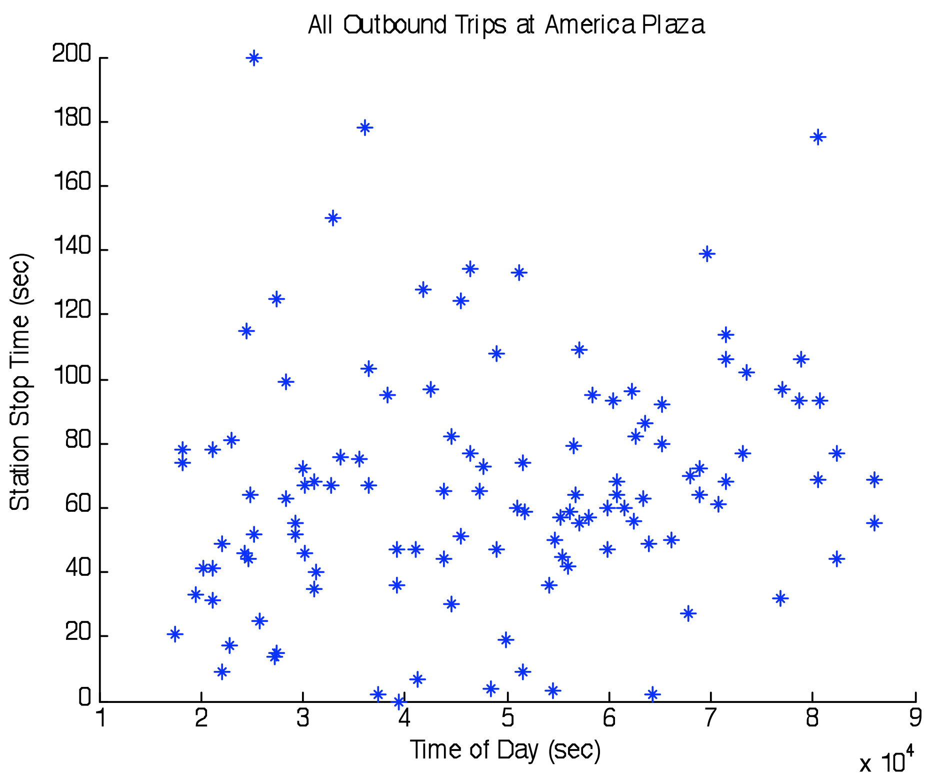

Figure 3-11 Distribution of dwelling time at America Plaza Station

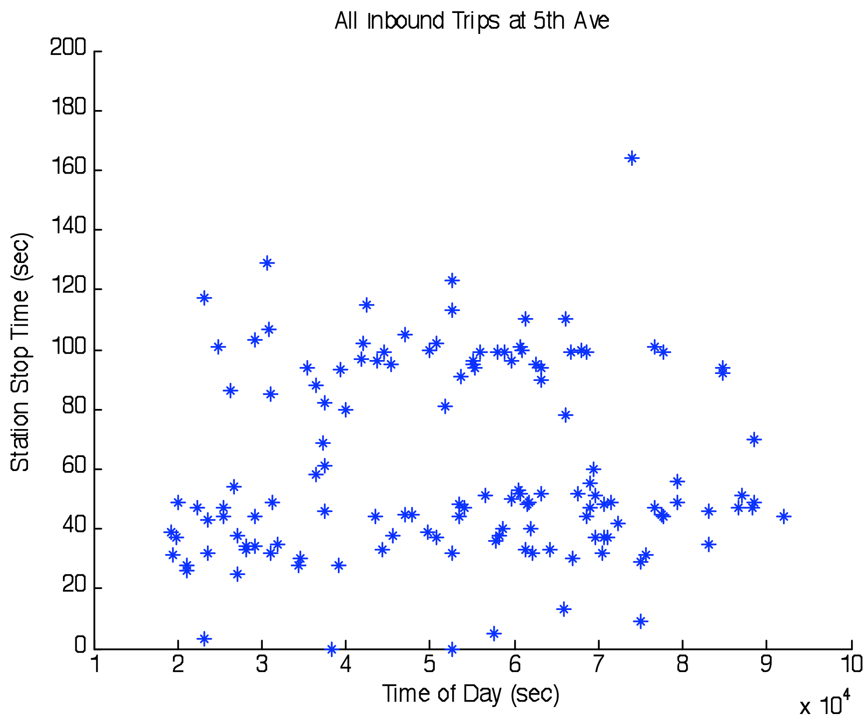

Figure 3-12 Distribution of dwelling time at 5th Ave Station

3.3.2.4 Analysis of Prediction Errors

The prediction errors are mainly contributed by four factors: passengers' activities, operator behavior, equipment accuracy, and traffic signal operations. Although detailed GPS trajectory data and traffic operation data are collected, the prediction error cannot be directly measured because the exact time when a trolley is ready to depart from a station is unknown. Here we analyzed the prediction errors by following four randomly selected sample trolley trajectories.

The first chosen trip was an outbound train entering the testing site at 6:59:54 on October 16. The first predicted time-to-arrival (TTA) to India Street started at 78 seconds. From 7:01:09 to 7:06:54 for 345 seconds, the train's GPS location almost did not move at all. It is totally different from the historical dwell time at America Plaza Station. The predicted TTA stayed at about 18 seconds from 7:01:09 to 7:04:27 and jumped to 34 seconds at 7:07:20. The reason for the failure prediction is the extensive long dwell time and possible bad GPS reception under the glass roof at America Plaza Station.

The second selected trip was an inbound trip started at 9:30:14 on October 16, 2009. The first predicted TTA to 11th Ave started at 69.5 seconds. The train didn't stop at signals before 11th Ave. and departed at 11th Ave station at 8:32:26. Given the historical dwell time of 31 second at City College and 21.6 seconds at Market Street, the prediction error is only 10 seconds and within 10%. The train left 11th Ave at the beginning of the green cycle. Because of the predicted 10 seconds early, the train stopped for about 5 seconds at 7th Ave and went through all other intersections without any stops.

The third picked trip was an inbound trip started at 10:23:06 on October 16, 2009. The predicted TTA to 11th Ave started at 67.5 seconds. The train didn't stop at the signal before 11th Ave but stopped at Market Street station from 10:23:26 to 10:24:21 for 55 seconds, which is much longer than the historical time of 21.6 seconds. The train departed 11th Ave at 10:26:37 at the beginning of the green cycle. Given the sum of two historical dwell times of 52.6 seconds, the prediction error can be 91 seconds. But the operator might stop the train to wait for a fresh green rather than take advantage of TSP. The waiting might take up to 70 seconds. Not surprisingly, TSP did not benefit the trolley operation for this trip. However, the impact on general traffic still existed.

The last picked trip was an outbound trip started at 14:10:51 on October 16, 2009. The predicted TTA to India Street started at 95.0 seconds. The trolley stopped from 14:11:39 to 14:13:05 for 86 seconds and then moved very slowly to reach India Street at 14:17:09, which is 378 seconds after the train enters the boundary of the testing site. Given the historical dwell time of 15.6 seconds and 21.3 seconds at Santa Fe and America Plaza, respectively, the predicted departure time is totally wrong. It is partially because of the extensively long dwell time at Santa Fe and also at America Plaza. Because the GPS was slowly moving, it is hard to tell when the train stopped at America Plaza. GPS was the issue under the roof at America Plaza station.

It is noted that the success of train arrival prediction would normally lead to a successful TSP implementation, as illustrated by the second picked trip. However, many cases have significant issues in predicting the departure time at those near-side stations. Some observations can be summarized here:

- Extensive long dwell time at stations (our observations underestimate dwell time in most cases)
- GPS reception issue at America Plaza due to the glass roof.
- Train might stop at crossings before arriving at America Plaza.
- Train might stop at signals before arriving at City College.

4. Recommendations and Next Step

The proposed system design can be easily applied to other light-rail transit (LRT) systems, which do not have the preempted right-of-way at grade crossings and intersections. It is not necessary to have fixed-timing control at the signalized intersections. The proposed concept and system can be easily adapted to actuated or semi-actuated control systems. Moreover, the results and lessons learned from both of the laboratory test and the preliminary field operational test could help in designing and calibrating such transit signal priority systems for other similar LRT systems.

The preliminary FOT has been completed. According to the data analysis, there are still many issues before a large deployment of the proposed ATSP system may be made. This section summarizes the issues and recommendations in order to further improve the system towards the next step. With all the system improvements and testing, a final FOT will be performed.

4.1 Signal Transition

As described in a previous report under Task Order 5407, the proposed adaptive signal control strategy (Scheme I) is used for those late trips, which account for about 10% of total trips. If the system capacity is required to be increased, say, there are 80% of trips, which are late or require adaptive priority, then the strategy shown in the previous section will fail to work. The major restriction results from the logic of signal controllers, in particular, signal transition logic.

In many cases, an additional cycle is required for signal controllers to complete the transition from one set of signal timings to another. Therefore, if the frequency of a priority request increases, then such a transition period becomes longer, which will have more negative impacts on the whole traffic system, e.g. unrequested trolleys and cross-street traffic.

In addition, due to the signal transition logic, the solution of the proposed adaptive signal control model may not be implementable in the field. For implementation, the signal timings in the current cycles may highly relate to the signal timings in the previous cycle.

There are at least two remedies to take into account the signal transition logic:

- Set up another model to obtain the signal timings for the transition cycle, such that the signal timings from the proposed adaptive signal control strategy are guaranteed to be implemented in the cycle after the transition;
- Put more constraints on the adaptive signal control model mentioned above, such that the signal timings from the modified adaptive signal control strategy are to be implemented in the cycle right after the one with base-line timings.

4.2 Signal Progression

The original signal progression design also impacts the performance and design of the TSP system. The better the original progression design requires little timing change to redesign the progression for approaching trolleys when given real-time trolley movement information. According to the field data, some segments actually suffer from the existing signal progression design. As shown in Figure 4-1 and Figure 4-2, many trajectories have to stop at intersections between stations due to inappropriate progression design. The progression results for other segments are included in the Appendix. Therefore, it is also important to redesign the signal progression before the large-scale implementation of the priority system.

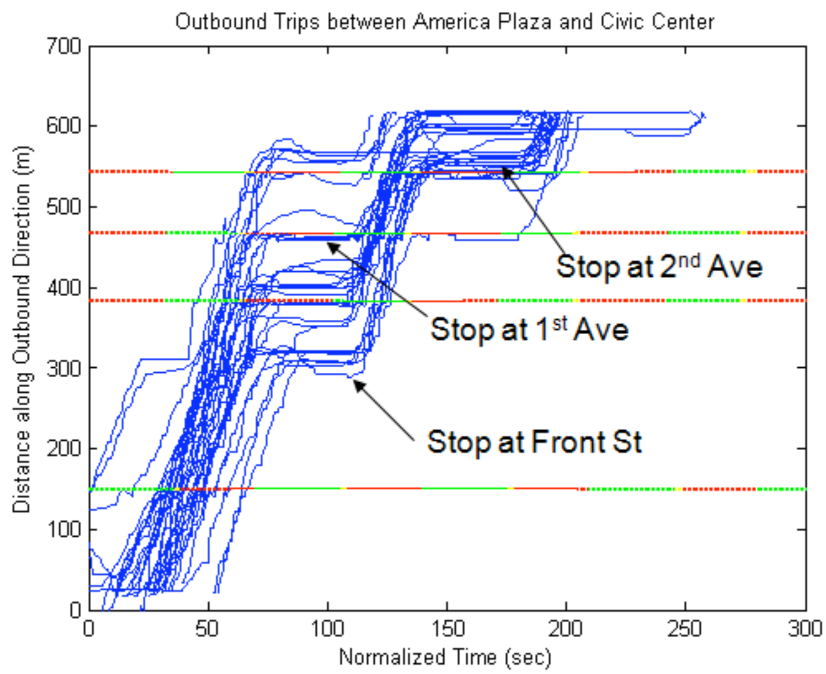

Figure 4-1 Outbound trajectories between America Plaza and Civic Center (No TSP)

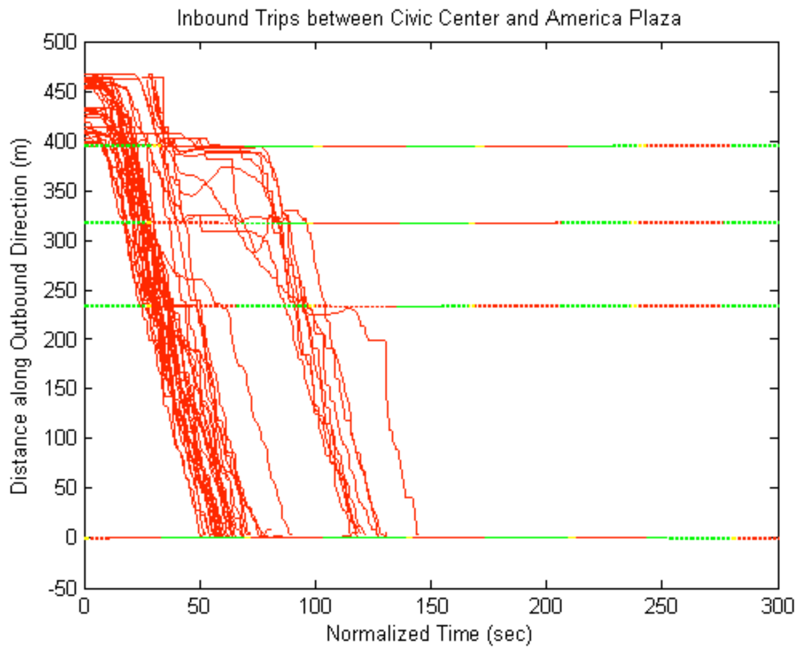

Figure 4-2 Inbound trajectories between Civic Center and America Plaza (No TSP)

4.3 Dwell Time Prediction

The proposed adaptive signal control strategy takes the trolley's predicted arrival time as one of the inputs. The effectiveness of the proposed strategy largely depends on the accuracy of the arrival time prediction. Unfortunately, few studies have been conducted on the prediction of station dwell time because there are so many uncertainties which make it impossible to obtain an accurate prediction. For example, if a handicapped person needs to board the trolley, the dwell time may be much longer (e.g. 2 or 3 more minutes) than usual. In addition, the downstream signal status also contributes to the dwell time of nearside stations.

However, a simple linear regression model based on limited observed field data is applied to predict the dwell time at each station. More data from the field are required to obtain more knowledge on the dwell time. Furthermore, the prediction of dwell time statistics, e.g. 95% percentile, is more tractable and pragmatic than the prediction of exact dwell time or the mean of dwell time. Due to the interaction between the trolley dwell time and the downstream signal status, it is more appropriate to optimize the signal timings by integrating them with dwell time prediction.

4.4 Trolley's Arrival Time Prediction at Station

As presented in the previous section of this report, the TSP benefits on trolley operation, particularly on trolley travel time, are not as expected. Under the existing ATSP strategy, the priority algorithm takes predicted trolley departure times at stations, the current signal status at downstream intersections and signal timing constraints as inputs to design a desired trolley green band. In order to have local controllers to execute the trolley green band timing, the timing decision needs to be made 2 minutes ahead of start time of the designed green band. Due to the variations of a trolley's intersection delay and dwell times at a station, a trolley often misses the designed green band.

The predicted trolley departure time at a station consists of two components, the predicted arrival time at a station and the predicted dwell time at a station. The trolley's intersection delay was not considered when providing the first component - the predicted arrival time at a station and a predetermined constant was used as the second component – the predicted dwell time at a station. The inability of the prediction algorithm in dealing with variations of trolley intersection delay and dwell time is the major cause of a trolley missing the designed green band.

Real-time signal status needs to be incorporated into the prediction algorithm to gain the ability of estimating a trolley's intersection delay. As a trolley does not share the road with general motor vehicles, it is reasonable to believe incorporating signal status will achieve a more accurate prediction.

4.5 Integrating Priority Decision with Prediction

Dwell time at a station has variability. Along the testing segment, the width of priority green band is usually less than 20 seconds, with a 60 second cycle length. It is not practical to precisely predict the dwell time so that it can meet the requirement of the priority algorithm. A more practical approach is to predict the probability of "can departure", conditional on the time window, the time from the predicted arrival time at station to the start time of the green band at the downstream intersection, and to integrate the priority decision with the prediction. This approach does not require to precisely predict a trolley's dwell time at a station but rather to influence a trolley's stop time at a station (combination of dwelling time and green signal waiting time) to minimize the travel time between stations.

To illustrate how influencing stop times at a station affects the probability of a trolley missing the green band, Figure 4-3 below shows the comparison of trolley stop time at City College station for westbound trips (left-side plot) and eastbound trips (right-side plot), under the without TSP scenario. There are two groups of blue bars in both plots. The group on the left side corresponds to trips upon departure at the coming green light while the group on the right side corresponds to trips that missed the coming green and waited for one more signal cycle.

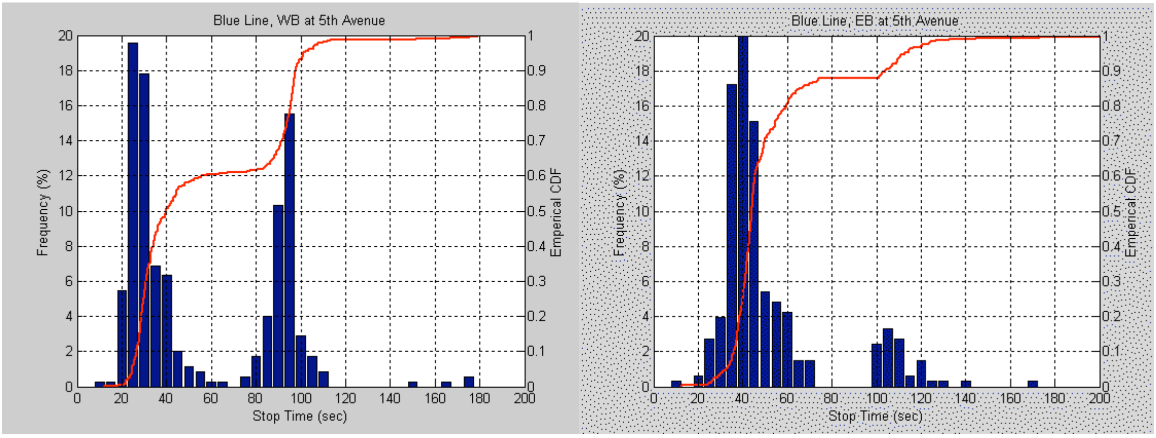

Figure 4-3 Trolley stop time at City College Station (No TSP)

Compared with westbound trips, eastbound trips have slightly longer stop times upon departure at the coming green and with much less chance of missing the coming green (10 percent vs. 40 percent). The difference in stop time distributions for west- and east-bound directions ties with the underlining signal timing. Figure 4-4 shows west- and east-green bands along the test segment. In the plot, westbound trips travel downward. At City College Station - the solid black line in the middle, the offset between the upstream green band and downstream green band on westbound is obviously smaller than that on eastbound. Westbound trips have less chance to finish passenger loading/alighting activities within the offset and therefore have a higher chance of missing the coming green band.

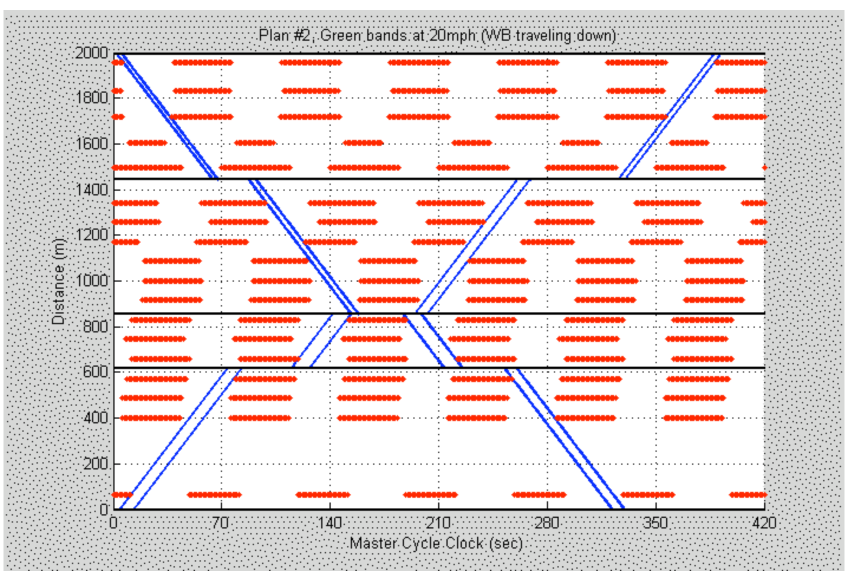

Figure 4-4 Green bands along testing segment (No TSP)

There is a tradeoff between signal waiting time at a station and travel time to the downstream station, i.e., the time from arrival at a station to arrival at its downstream station. The longer the waiting time is, the higher the chance that a trolley could hit the designed green band but could result in longer travel time to the downstream station. The integrated approach dynamically makes the tradeoff decision to minimize the total travel time.

4.6 Automatic Vehicle Location (AVL) System

The cellphone-based cost-effective AVL system in the preliminary FOT is not successful due to the serious “urban canyon” effect. A better solution should be proposed and/or tested. At the beginning of the project, another type of AVL system based on a GPRS modem and GPS receiver with external antenna was tested. As shown in Figure 4-5, the trolley trajectories are more stable and closer to the geometry street map when compared with the results from the cellphone-based system. Such a system with an external GPS antenna can be a potential solution for future testing. However, more testing is still needed before the next FOT, particularly at the area around America Plaza Station where the existing system performed the worst.

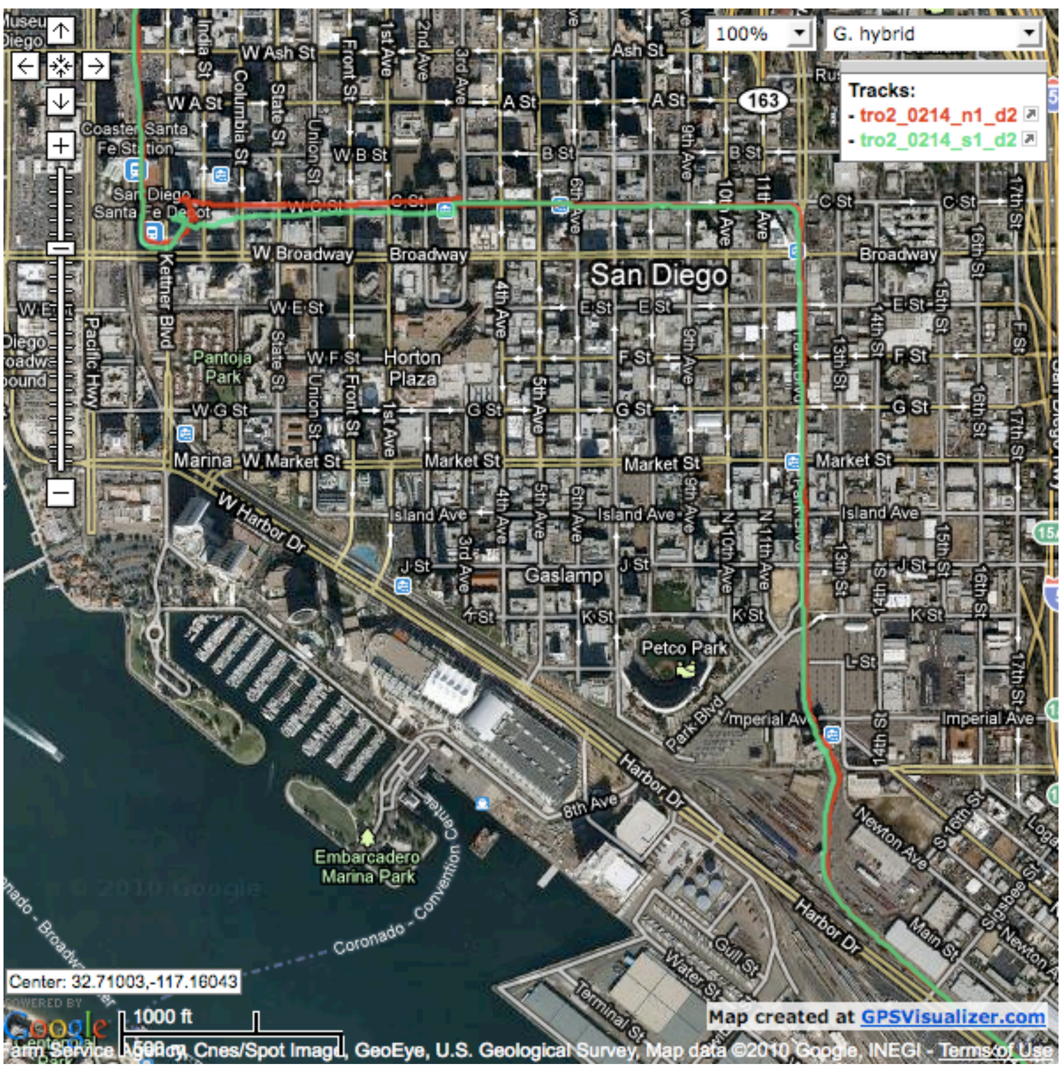

Figure 4-5 GPS receptions with GPS external antenna

Appendix

Table 5-1 Detailed trip samples for Stage 1 without TSP

Date	*Trolley #1*		*Trolley #2*		*Trolley #6*		*Trolley #8*		*Summary*	
	OB	IB	OB	IB	OB	IB	OB	IB	OB	IB
30th	0	0	0	0	1	2	6	8	7	10
31st	0	0	0	0	0	0	0	0	0	0
1st	0	0	0	0	0	0	6	7	6	7
2nd	0	0	0	0	3	4	6	7	9	11
3rd	1	1	0	0	2	3	2	4	5	8
4th	1	2	3	2	3	3	4	5	11	12
5th	1	2	0	1	3	4	7	8	11	15
6th	1	2	6	7	3	4	9	8	19	21
7th	0	0	0	0	0	0	5	6	5	6
8th	0	0	5	6	0	0	2	2	7	8
Sum.	4	7	14	16	15	20	47	55	81	98

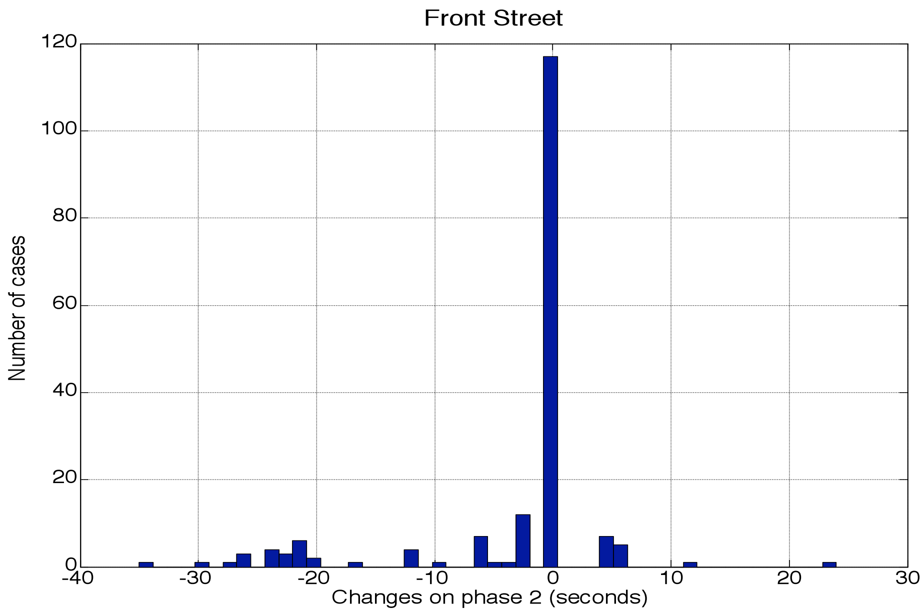

Figure 5-1 Changes on phase 2 (trolley) at Front Street

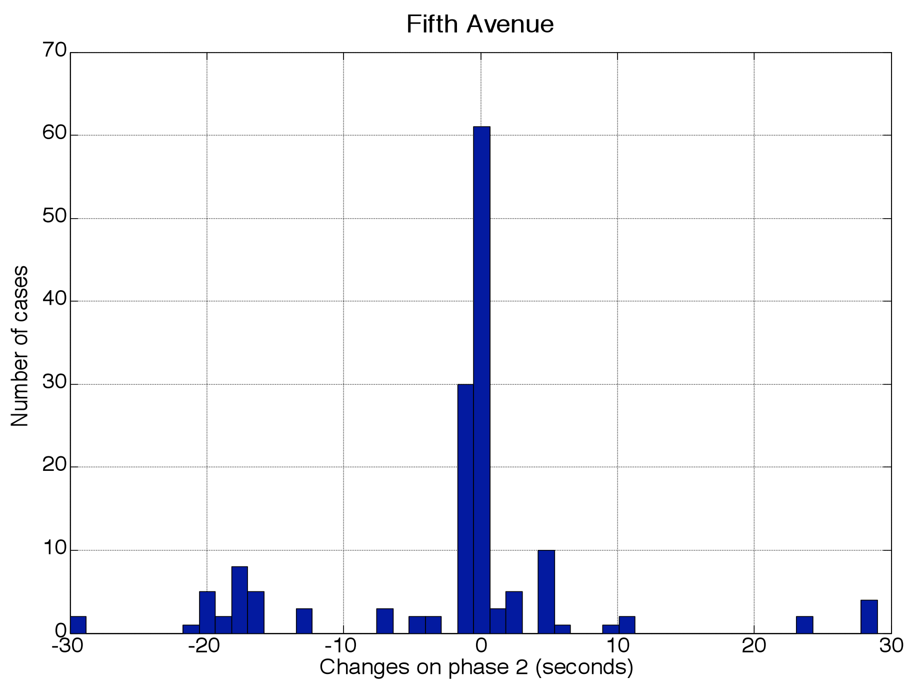

Figure 5-2 Changes on phase 2 (trolley) at 5th Street

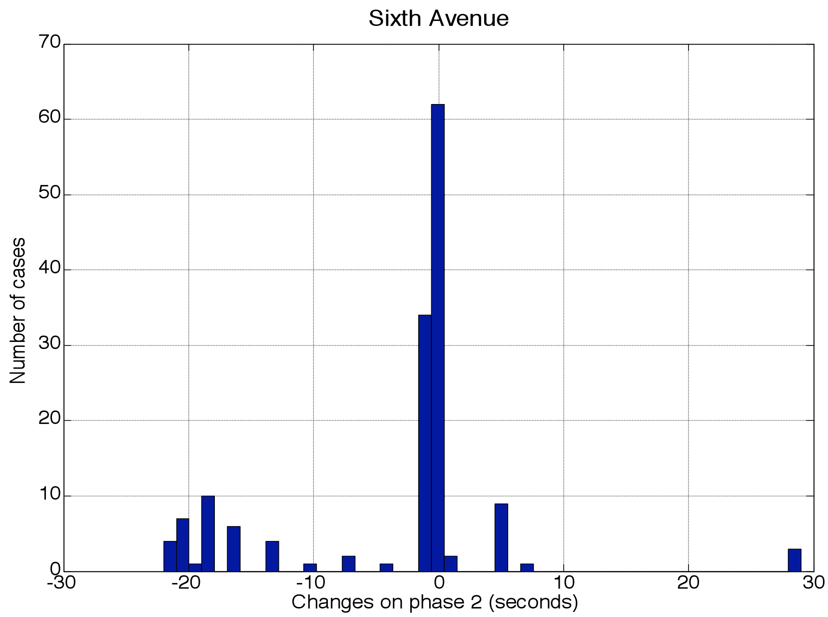

Figure 5-3 Changes on phase 2 (trolley) at 6th Street

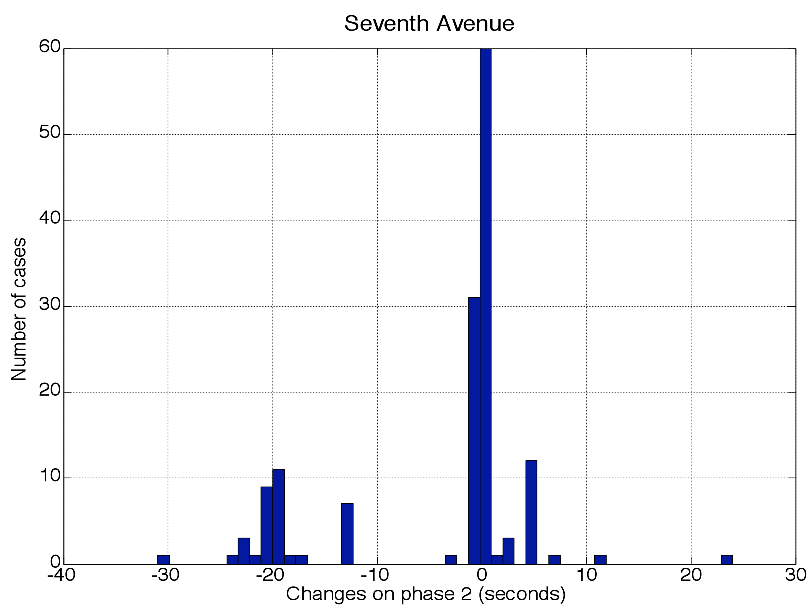

Figure 5-4 Changes on phase 2 (trolley) at 7th Street

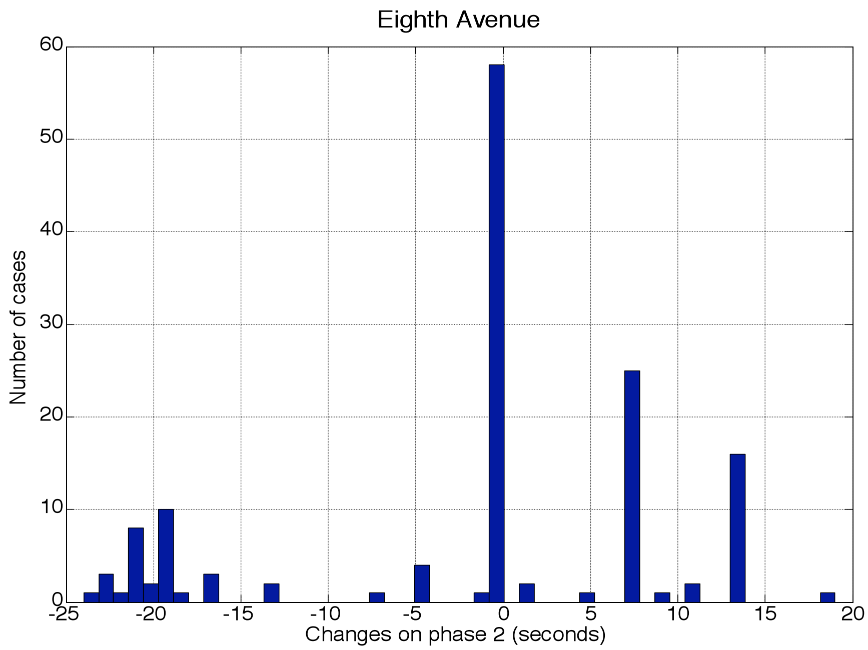

Figure 5-5 Changes on phase 2 (trolley) at 8th Street

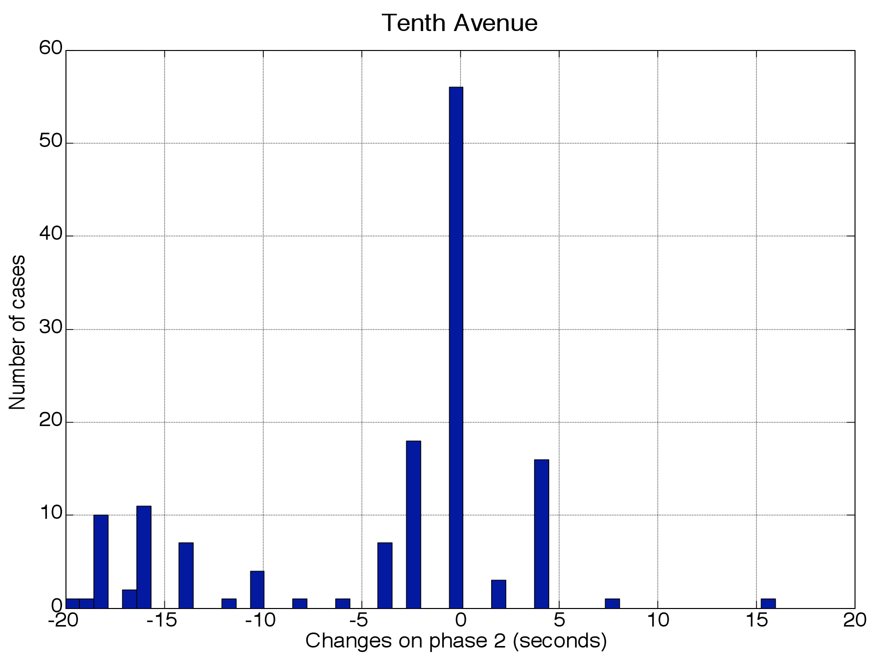

Figure 5-6 Changes on phase 2 (trolley) at 10th Street

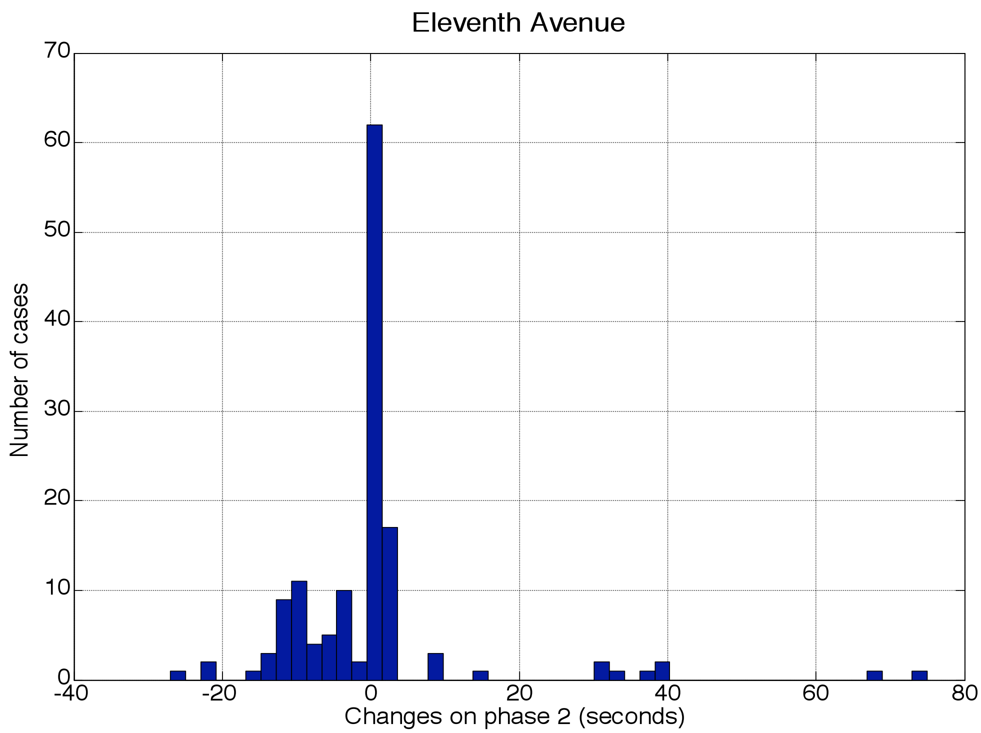

Figure 5-7 Changes on phase 2 (trolley) at 11th Street

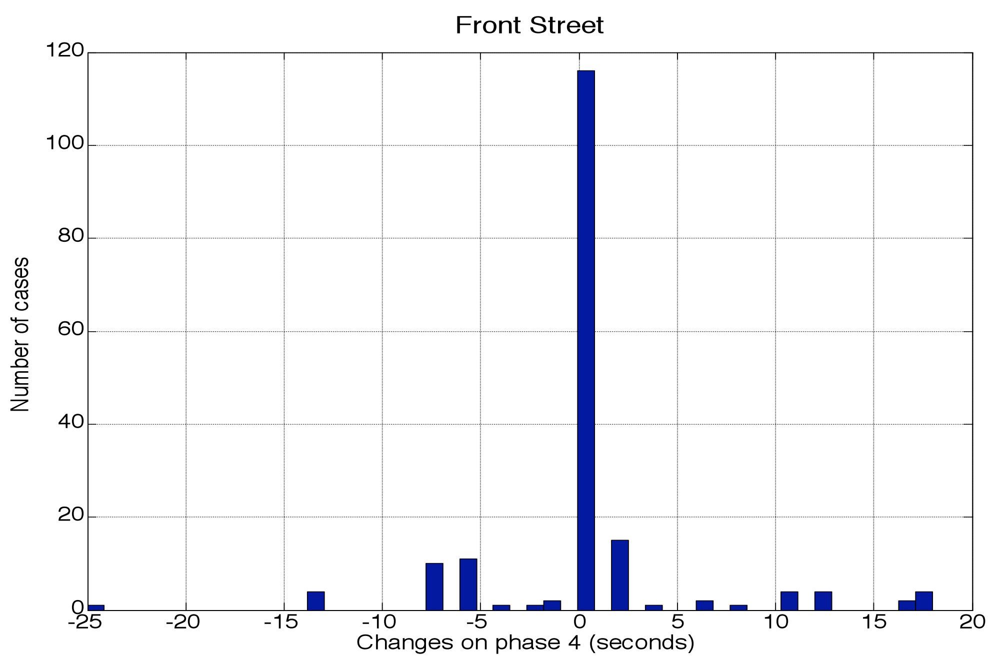

Figure 5-8 Changes on phase 4 (trolley) at Front Street

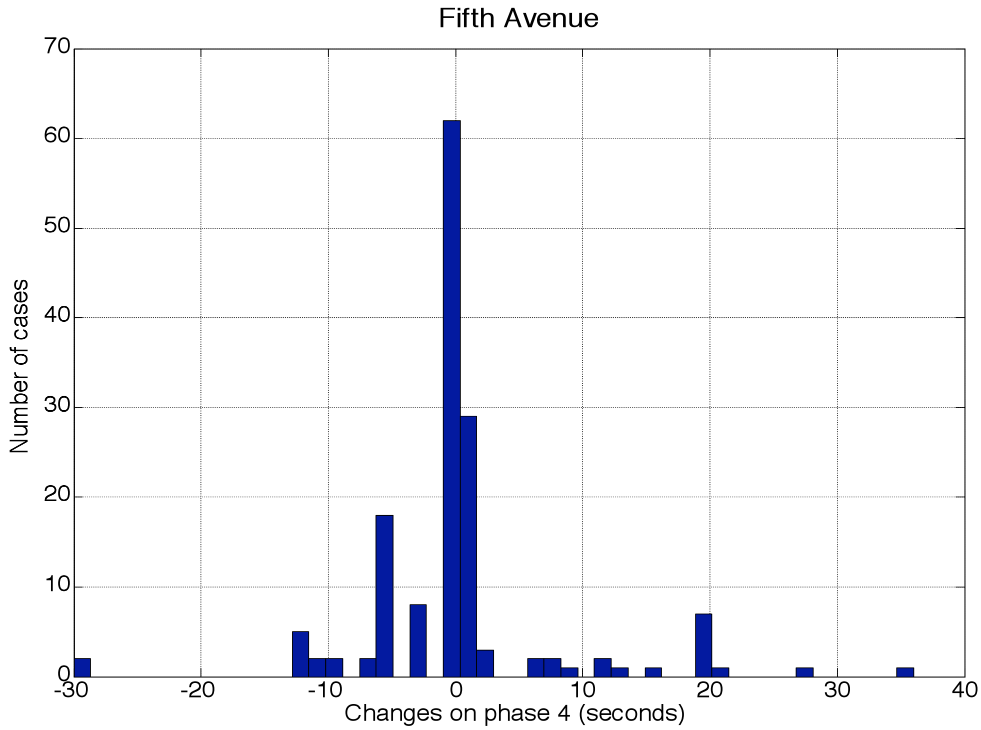

Figure 5-9 Changes on phase 4 (trolley) at 5th Street

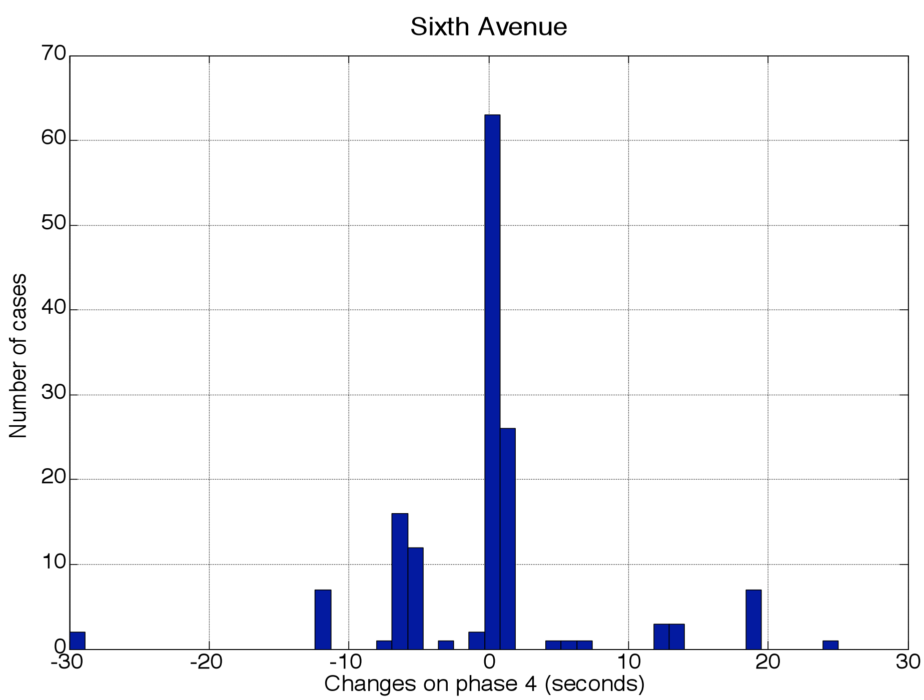

Figure 5-10 Changes on phase 4 (trolley) at 6th Street

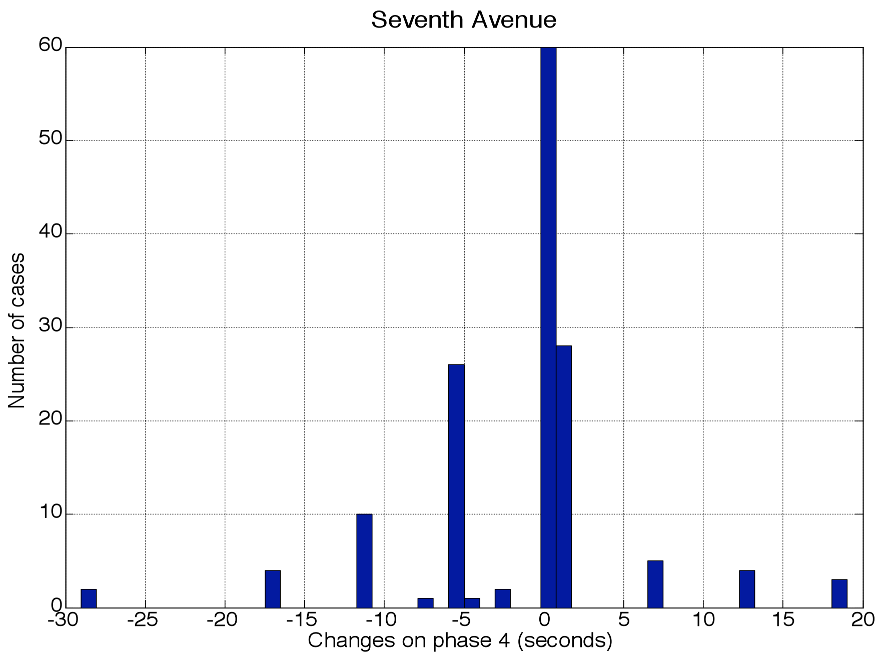

Figure 5-11 Changes on phase 4 (trolley) at 7th Street

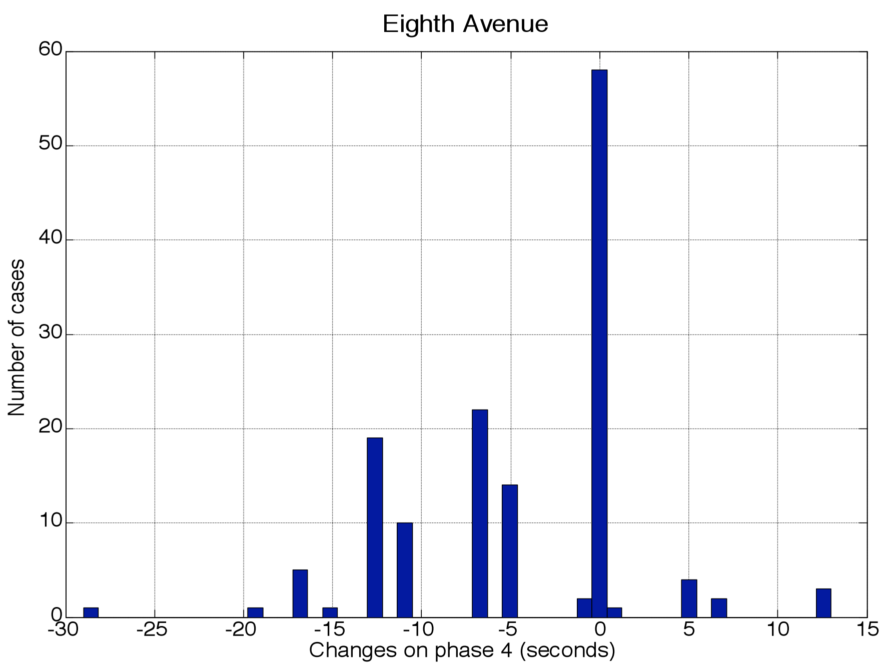

Figure 5-12 Changes on phase 4 (trolley) at 8th Street

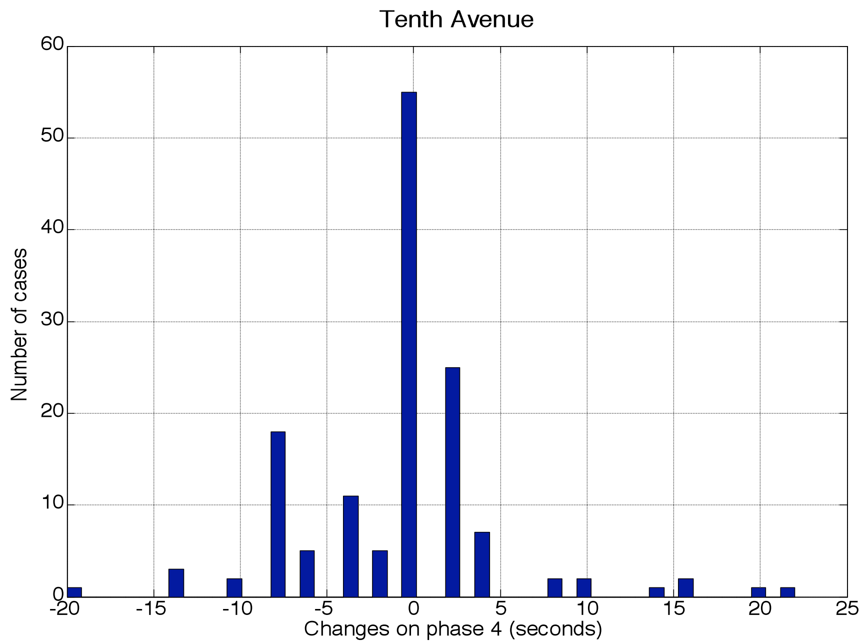

Figure 5-13 Changes on phase 4 (trolley) at 10th Street

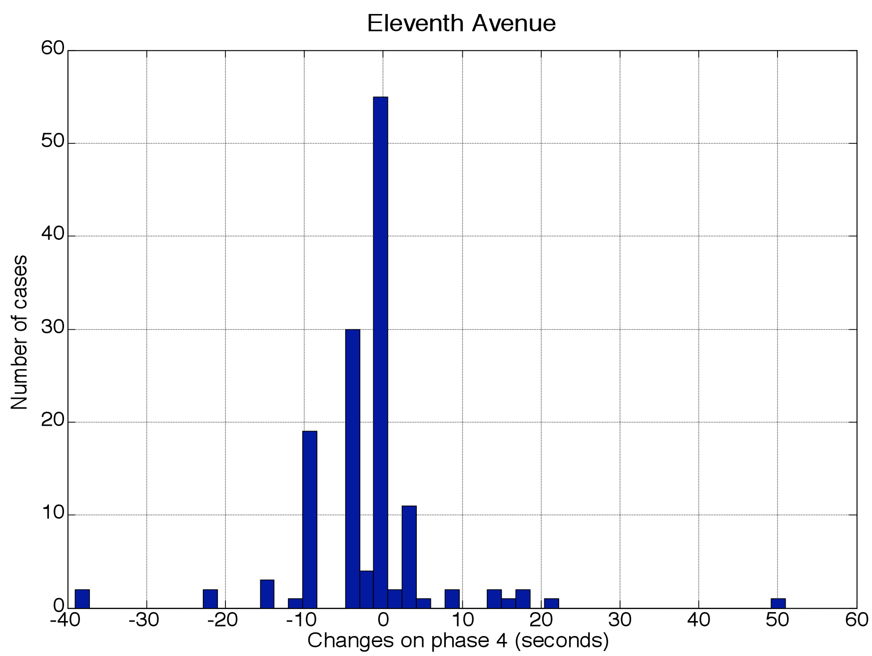

Figure 5-14 Changes on phase 4 (trolley) at 11th Street

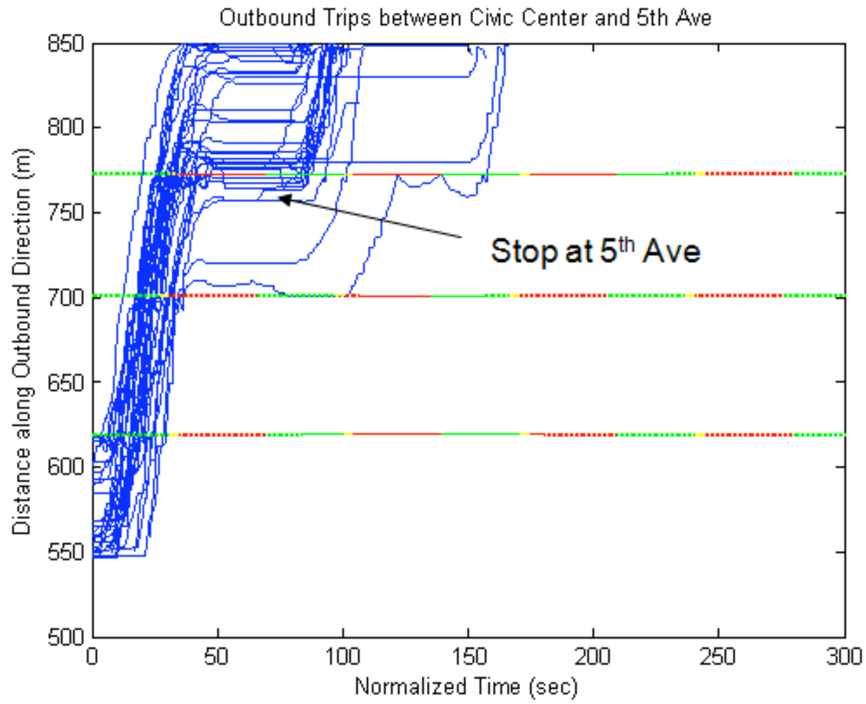

Figure 5-15 Outbound trajectories between Civic Center and 5th Ave (No TSP)

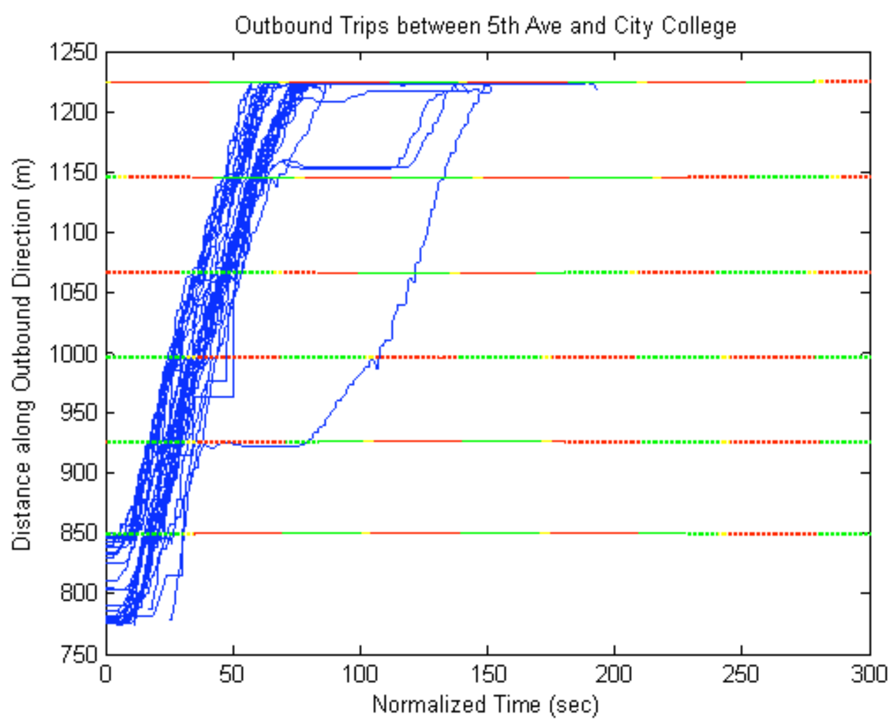

Figure 5-16 Outbound trajectories between 5th Ave and City College (No TSP)

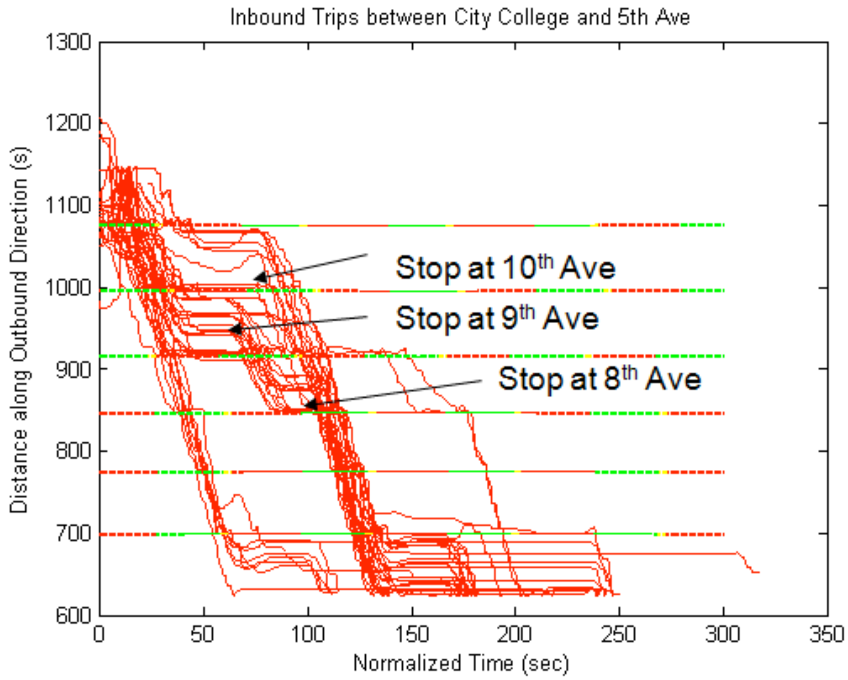

Figure 5-17 Inbound trajectories between City College and 5th Ave (No TSP)

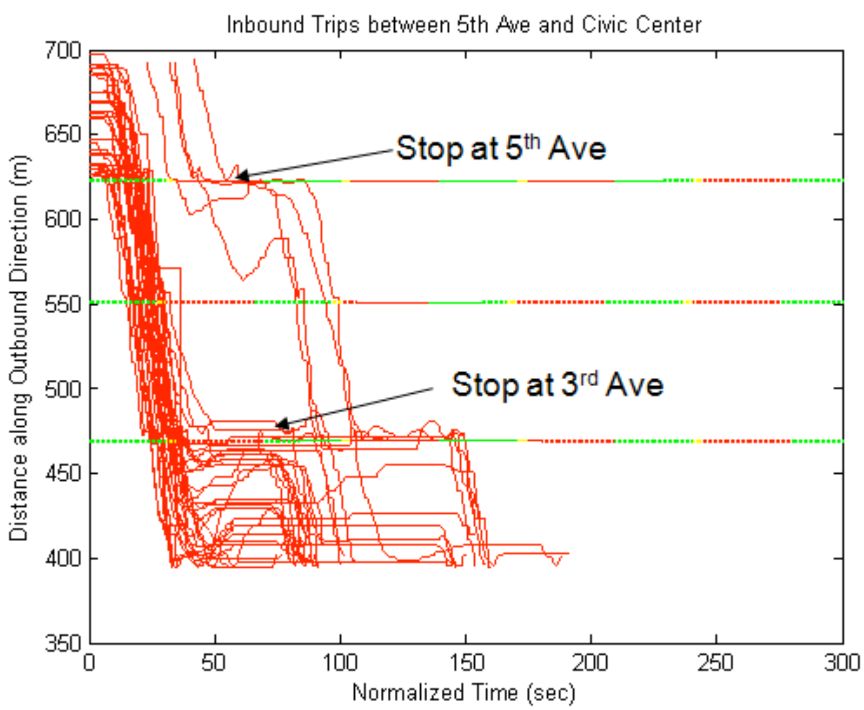

Figure 5-18 Inbound trajectories between 5th Ave and Civic Center (No TSP)