TRANSIT SIGNAL PRIORITY
FOR THE
SAN FRANCISCO MUNICIPAL TRANSPORTATION AGENCY

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Master of Science in Engineering

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Dedicated to Frances McCormick

Frances and I worked hard to have this project in a shape where it is right now. It was her dream to complete this project. Unfortunately, she is not among us to represent her work. But I am sure she must be very proud of her accomplishments including this project. It couldn’t be possible for me to present this project without her huge contribution to the project. She was a partner, a guide, an inspirational source, and most of all, a great friend.

I would like to dedicate this entire project to her.
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ABSTRACT

Transit Signal Priority (TSP) is a traffic management system implemented in urban mass transit centers around the world. It is viewed as a viable way to help public transportation agencies operate their systems more efficiently by reducing travel time and traffic congestion. TSP also improves air quality and energy consumption, helping to create a sustainable public transportation system. The research conducted highlights the benefits of public transportation, describes TSP in detail, and reviews case studies in Los Angeles, California and Zurich, Switzerland.

This study further investigates various TSP technologies for the San Francisco Municipal Transportation Agency (SFMTA). In response to a Request for Information (RFI), five companies completed a survey describing their technologies. The vendors also participated in demonstration tests that validated the effectiveness of their equipment. Based on the data collected in the surveys and during testing, seven design criteria were rated. Applying decision matrix analysis, the companies were also rated according to their ability to meet the criteria. The company using the preferred technology has the highest score.

Economic analysis results in a benefit cost (B/C) ratio of 3.6 and return on investment (ROI) of 2.7 years indicating that TSP is a viable solution. The overarching objective was to select a TSP system that would demonstrate a 10% improvement in travel time for one of SFMTA’s main bus routes. However verification could not be determined due to project time constraints. Proving actual savings in transit travel times is recommended as further work.
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Shilpa Gorde
Frances K. McCormick, P.E.
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1 INTRODUCTION

In metropolitan cities, the demand for mobility is on the rise. This growth in demand exerts pressure on the existing transportation infrastructure, and poses a complex network of social, economic, and physical challenges for public transportation systems. For example, as areas of a city are redeveloped, the need to establish new transportation lines typically emerges. However, this perceived need is mitigated by other forces that include fiscal considerations, anticipated ridership, impact on non-public transit traffic patterns, and environmental effects. Each of these areas needs to be carefully assessed before undertaking major transportation projects, such as the implementation of a new public transit route. An alternative to such major overhauls is to operate existing public transit systems more efficiently. The implementation of a Transit Signal Priority (TSP) system, that manages traffic patterns and thereby facilitates the efficient operation of public transit vehicles, is one cost effective way to modify existing transit routes. In addition to helping public transportation agencies operate their systems more efficiently, TSP can reduce travel time and traffic congestion, and improve air quality and energy consumption. Overall, TSP can help to create sustainable public transportation.

This project investigates various TSP systems for the San Francisco Municipal Transportation Agency (SFMTA). Since an important source of delay for public transit passengers is due to buses being stopped at red lights, SFMTA wants to try to minimize such delays, making public transportation more viable than single occupancy cars. One inexpensive method for reducing transit delay is to implement TSP. TSP systems, provided to SFMTA by various companies for demonstration purposes, are compared to
ascertain the most sustainable one for the SFMTA, i.e. which system will enhance
regional mobility by improving transit travel times. The overarching objective is to select
a TSP system that will demonstrate a 10% improvement in travel time for one of
SFMTA’s main bus routes.

1.1 Project Scope

This project investigates various TSP systems for the San Francisco Municipal
Transportation Agency (SFMTA). Specifically, several systems provided by industry
vendors are compared to ascertain which system will most enhance regional mobility by
improving transit travel times. The overarching objective is to select a TSP system that
will demonstrate a 10% improvement in travel time for one of SFMTA’s main bus routes
known as the “16 Mission”. This improvement, if obtained, will both improve quality of
ridership experience and enhance SFMTA sustainability efforts toward a greener, more
fuel-efficient, operating system.

In order to assess whether or not a 10% improvement in travel time can be
achieved, a series of demonstration tests will be conducted. Initially, surveys containing
the required design parameters will be sent to leading industry vendors. Once completed,
a matrix will be developed to select the most promising systems. Then actual
demonstration tests will be conducted in three parts:

1. Attach vendor’s equipment onto a van and equip several intersections with radio
or wireless fidelity (WiFi) receivers connected to controllers to implement priority
calls.
2. Configure the equipment such that it can be installed on a live transit vehicle, including a fire engine, to demonstrate its use there.

3. Quantify the impact based on a number of performance standards.

1.2 Concurrent Engineering and the Project Schedule

A schedule has been developed for the project in order to track individual tasks and highlight milestones. The schedule is shown in Appendix A.

Concurrent Engineering is used as a framework to simultaneously engineer the planning, design, and implementation phases of the project. According to Anderson (2008), Concurrent Engineering is the practice of concurrently developing products and associated manufacturing processes. In the TSP for SFMTA Project, a multifunctional team was formed “with all specialties present and active early”. The Project team consisted of two-TSP team members, four members from the SFGo team, a D4 Software Consultant, two Electricians, and one Traffic Signal Engineer. They represented different functions such as program management, engineering, reliability and maintainability, testability, and quality. The decision about technology to employ for SFMTA is a consensus of all the team members.

The TSP for SFMTA Project consists of three major phases: Planning, design, and implementation. Planning and design phases are conducted concurrently. While economic justification and analysis is done in planning phase, the design team is proceeding with the assessment of possible technologies and live demonstration tests.
Similarly, the design and implementation teams are working simultaneously. While the design team surveys existing vendors, it is also researching design parameters to define a TSP system that will serve SFMTA’s needs.

Concurrent engineering enables the SFMTA Project team to get it right the first time. According to Stark (1998), getting the design correct at the start of the process will reduce downstream difficulties. The need for expensive engineering changes later in the cycle will be reduced. By involving team members such as Electricians during the design phase, expensive maintenance costs are reduced. The overall design cycle time is optimized through active feedback. Concurrent Engineering aims to reduce the number of redesigns, especially those resulting from post-design input from support groups. By involving these groups in the initial design, less iteration are needed. The major iterations that do occur will occur before the design becomes final.
2 LITERATURE REVIEW

2.1 The Benefits of Public Transportation

In order to investigate the effective optimization of a public transportation system, it is helpful to first assess the benefits (and limitations) of public transportation in and of itself. In general, public transportation is beneficial to the economy and the environment. GRITS (Green River Intra-County Transit System, www.ridegrits.org, 2006) is an organization for the Audubon Area of Kentucky that provides safe, reliable public transportation to special populations in regions where there are no other public transportation options. In their 2006 website article, “Public Transportation…An investment for the future,” GRITS identifies a host of benefits that public transportation provides. These benefits and corresponding supporting facts are detailed in Table 1.

Table 1: The Benefits of Public Transportation

<table>
<thead>
<tr>
<th>BENEFITS</th>
<th>FACTS</th>
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<tbody>
<tr>
<td>Stimulates the Economy</td>
<td>• Every dollar taxpayers invest in public transportation generates $6 or more in economic returns.</td>
</tr>
<tr>
<td></td>
<td>• Every $10 million in capital investment in public transportation yields $30 million in increased sales.</td>
</tr>
<tr>
<td></td>
<td>• Every $10 million in operating investment yields $32 million in increased sales.</td>
</tr>
<tr>
<td>Saves Money</td>
<td>• For every $10 million invested in public transportation, more than $15 million is saved in transportation costs to both highway and public transportation users.</td>
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<td>• The estimated cost of driving a single-occupant vehicle is between $4,826 (for a small car) and $9,685 (for a large car), depending upon mileage. By contrast, the annual average cost for public transportation for one adult ranges from $200 to $2,000, depending upon</td>
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<td>Category</td>
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| Creates Jobs                     | • In 2000, 350,000 people are directly employed by public transportation systems, and thousands of others are employed in related support services (i.e. engineering, manufacturing, construction, retail, etc.)  
• For every $10 million invested in capital projects for public transportation, more than 300 jobs are created and a $30 million gain in sales for business is realized. |
| Gets People to Work              | • Public transportation is key to moving former welfare recipients into the workforce as permanent wage earners. An estimated 94% of welfare recipients attempting to move into the workforce do not own cars and rely on public transportation.  
• Public transportation provides valuable options for suburban commuters who work in the city. In fact, the average annual income of rail commuters is more than $50,000 and most own two cars. |
| Eases Traffic Congestion         | • Public transportation helps to alleviate our nation’s crowded network of roads by providing transportation choices. Without transportation choices, there would be 64,413 more cars on the road in New Orleans, 167,061 more cars on San Diego roads, and 2,610,280 more cars on New York City roads.  
• In Portland, Oregon, when more transportation options are offered, people use their cars less, thereby cutting traffic by 6% and traffic delays by 66%. |
| Fosters More Livable Communities | • The ability to travel in an area conveniently, without a car, is an important component of a community’s livability.  
• Public transportation provides opportunity, access, choice and freedom, all of which contribute to improved quality of life. |
<p>| Boosts Real Estate Values        | • There are greater increases in the value of properties located near public transportation systems than in |</p>
<table>
<thead>
<tr>
<th>Benefits</th>
<th>Description</th>
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| Improves Air Quality                         | • Each year, public transportation use avoids the emission of more than 126 million pounds of hydrocarbons, a primary cause of smog, and 156 million pounds of nitrogen oxides, which can cause respiratory disease.  
  • Buses emit 80% less carbon monoxide than a car; rail, almost none. |
| Reduces Energy Consumption                   | • Public transportation can significantly reduce dependency on gasoline, reducing auto fuel consumption by 1.5 billion gallons annually.  
  • Many U.S. transit systems are continuing to invest in compressed natural gas, low-sulfur burning buses or diesel-electric hybrid buses. |
| Ensures Safety                               | • Riding a transit bus is 91 times safer than car travel. By train, passengers are 15 times safer.                                                                                                          |
| Enhances Mobility During Emergencies         | • On September 11, 2001, the New York-New Jersey Port Authority transit systems moved people safely away from the World Trade Center disaster.  
  • Public transportation systems have operated around the clock to transport firefighters to sites of wildfires; to evacuate nursing homes and hospitals; to move people to safety during storms; and to bring out-of-town police and rescue workers from airports. |

(www.ridegrits.org, February 2006)

Given the breadth and diversity of benefits of public transportation, utilization is on the rise. People from all social and economic backgrounds are turning to public transportation as a viable resource to travel to work, school, and recreation activities. In turn, the demand for public transportation agencies to improve service and reliability is increasingly critical.
2.2 Introduction to Transit Signal Priority

Transit Signal Priority is an operational strategy used to manage traffic and facilitate the movement of public transit vehicles through traffic-signal controlled intersections (U.S. DOT, 2005). Essentially, TSP senses oncoming public transit buses, streetcars, or light rail vehicles, and either turns the traffic light green or holds the traffic red light in order to improve transit performance.

Figure 1: Simplified TSP Block Diagram (Source: U.S. DOT, 2005)

Figure 1 is a simplified block diagram illustrating TSP main components. TSP works as a communication media in between buses and the traffic signal. The traffic signal can recognize that the bus is approaching the intersection ahead of time so the bus will spend less time on the red light. The transponders or routers are mounted on the bus which sends the signals to the traffic controller. This will keep the green light extended so that buses will pass the intersection without stopping or with a minimum wait period. If the light is red, the traffic signal controller gets a signal from the approaching bus and triggers the light to change from red to green.
The following steps, in general, describe a TSP system and are shown in Figure 2:

1. A bus approaches an intersection and at some point, Pa, sends a signal to the traffic controller, C.
2. The traffic controller, upon receiving the signal that the bus is at Pa, changes the traffic light to green.
3. As the bus passes through the intersection at point Pb a signal is sent to the traffic controller and the traffic controller resumes its previous timing sequence.

Figure 2: A Simplified TSP System (Source: U.S. DOT, 2005)

2.3 Types of Transit Signal Priority

According to the TSP Planning and Implementation Handbook (US DOT, May 2005) there are two basic types of transit signal priority—passive and active. Both relate to the implementation of TSP and are briefly described below:

2.3.1 Passive Transit Signal Priority

This system does not require any hardware or software. It works continuously on the knowledge of bus route and bus schedule. For example, the signal takes advantage of
bus stop locations so that the bus can load and unload passengers on red and will pass the intersection on green. The implementation cost is very low. This type of TSP system can either improve traffic flow or cause unnecessary delays, depending on the volume of traffic.

2.3.2 Active Transit Signal Priority

The active TSP system consists of a traffic signal program that changes the light from red to green for approaching transit vehicles. It can use techniques within the traffic control environment such as green extension, early green, and actuated transit phases, to allow buses to by-pass already waiting traffic.

A green extension extends the green light only when a transit vehicle approaches. It does not change the signal timing phase but merely holds the green light green for the oncoming bus to travel through the intersection. This technique works only if the light is already green as the transit vehicle approaches.

In contrast, an early green technique only works if the light is red as the transit vehicle approaches. It shortens the green light seen by the opposing traffic, and consequently, truncates the red for an early green display.

The third active TSP strategy, called actuated transit phase, only occurs when a bus is detected at the intersection. Examples include exclusive left turn lanes, queue jump phase, phase insertion, and phase rotation.

As its name suggests, exclusive left turn lights only appear when a bus reaches the intersection. Otherwise, there is no apparent left turn signal.
Phase insertion refers to a special priority phase that is inserted within the normal signal sequence. For example, when a transit vehicle approaches a light, a left turn signal will illuminate regardless of the phase sequence.

Conversely, a phase rotation means that the sequential order of the lights changes or is rotated.

Lastly, “a queue jump lane is a short stretch of bus lane combined with traffic signal priority. This lane enables buses to by-pass waiting queues of traffic and to cut in front by getting an early green signal. A special bus-only signal may be required.” (Calccit.org, 2009)

2.4 Detection Techniques

Active TSP also requires detection techniques to detect the arrival of the transit vehicle to the traffic signal. For effective traffic signal priority, the traffic signal needs information from the approaching transit vehicles, such as the arrival time or speed of the bus. The traffic signal needs to get this information ahead of time in order to manipulate the operation to avoid delays. Transit signal priority uses the detectors for this purpose.

According to Paul Olson, P.E., Intelligent Transportation Systems Engineer at the Western Resource Center of the U.S. DOT Federal Highway Administration, there are three different detection systems: zone detection, point detection, and continuous detection. In general, zone detection applies when the vehicle is within the fixed area prior to the intersection. For point detection, the bus is recognized at a fixed point. The continuous detection technique consists of the bus sending information to the signal at spaced intervals. All three are briefly described below.
2.4.1 Zone Detection

In this type of detection the controller will inform the traffic signal that the bus is in the zone. The zone is nothing but the strength of the signal from the transit bus as it approaches the traffic signal. This detection system was originally used by the railroad and emergency vehicles and controlled the signal for safety purposes. The advantage of this operation is that it will hold the signal green or flashing red for the approaching vehicle. There are two types of zone detection signaling – optical and radio frequency.

In optical signaling the signal will remain green or “ON” until the optical signal is lost. The optical signal is lost when the bus passes the intersection. The vehicle detection distance is not fixed—it can vary depending upon the vehicle and the intersection and could be affected by a dirty lens, source age, and weather conditions.

Currently, the San Francisco downtown Third Street Light Rail system uses a fiber optic line that interconnects the intersections. Peer-to-peer signal priority is implemented whereby the optic line informs two to three intersections ahead of time that the train is approaching. Another advantage of the peer-to-peer TSP is that it gradually changes the signal timing for the approaching trains and is safer than just giving priority adjustments.

With radio frequency signaling the system uses a transmitter and receiver unit. To adjust the zone detection, the receiver sensitivity can be changed and reset. This system provides information on the direction that the bus or the vehicle is coming from.
2.4.2 Point Detection

According to Olson (1999) the point detection system is currently being used in San Francisco for signal priority for both transit and emergency vehicles. The system uses Automatic Vehicle Identification (AVI) tags and the device transmits vehicle data with the use of loop detectors.

According to Shanteau (2009), a loop detector is a traffic loop installed in the pavement that detects metal objects like a bus, car, or bicycle, based on a change in inductance. This loop causes a change in resonant frequency, which is detected and sent to the signal controller.

Point detection will only help find that the vehicle was at certain fixed point at a certain time, but it will not ascertain its exact location. The main problem with this system is that no other information is provided to the controller besides the vehicle’s location at a single point in time. It does not account for any delays that the vehicle might experience past that point before reaching the signal.

2.4.3 Continuous Detection

According to Olson (pg.18), continuous detection systems provide a direct two way communications link between the transit vehicle and the traffic signal controller. The traffic signal controller receives information about the vehicle at certain time intervals. The time interval depends upon the timing parameters of the signal. For example, the time interval could be every three seconds. With this information the traffic signal controller can predict with greater accuracy the vehicle arrival time at the intersection.
2.5 Current Status of TSP in San Francisco

According to Fleck (2007), San Francisco has gradually been implementing some form of passive TSP since 1973. The track switches for Cable Cars have been in use for 25 years and pre-empt the traffic signals along their route. In the late 1980’s, the City started to convert the electromechanical controllers to solid state. Then the first TSP was implemented on the J-Church bus route. And in the 1990’s, TSP was installed along the Embarcadero and King Street.

San Francisco also uses fiber optic and infrared emitters on selected buses and intersections. The infrared emitters are fixed on the bus and notify the receivers on traffic signals that the bus is approaching that intersection, one intersection ahead of time. The disadvantage of the infrared emitter is that it requires line-of-sight clearance between the emitter and detector. The infrared emitter also requires fine-tuning which incurs higher maintenance costs.

To overcome these issues with infrared emitters, the SFMTA decided to use a Global Positioning Satellite (GPS) system. They are currently using GPS on emergency fire trucks. GPS is advantageous because it provides more flexibility for vehicle detection and does not require line of site communication between the bus and the signal receiver. The speed of the emergency vehicle can also be calculated to adjust the arrival time at the light. Figure 3 depicts TSP with a GPS system.
In 2003, D4 traffic signal software was adopted with type 2070 signal controllers. According to Fleck (2007), D4 includes the most advanced transit signal priority features on the market. As of April 2009, approximately 400 D4s have been deployed in the City of San Francisco. “The D4 specializes in easily configurable advanced actuated signal control and transit signal control (including of a kind cable car priority / preemption.) The D4 has a unique combination of features for optimizing fixed time or actuated control under both coordinated and free operations” (www.4dtraffic.com).

2.6 Factors Causing a Reduction in TSP Benefits in San Francisco

According to Fleck (2007) there are several issues that may reduce TSP benefits. These include close headway streets, close grid, conflicting transit routes, conflicts with major arterials, and near side bus stops.
2.6.1 Close Headway Streets

In San Francisco some streets like Market Street, have close headways. It is tough to implement TSP concepts on these streets. With close headways, it is difficult to give priority to the public transportation vehicle. They are trying to use Active TSP on Market Street.

2.6.2 Downtown Streets on a Close Grid

Implementing TSP on Third Street is also not feasible as it has a long artery. Also, one-way streets in downtown San Francisco have some factors that affect signal timing.

2.6.3 Conflicting Transit Routes

In San Francisco some intersections are very busy from traffic in both directions. Use of TSP on such busy streets is a special challenge for the SFMTA. In busy hours people find heavy traffic on these streets. They experience delay in their travel time. Determining the approximate number of passengers traveling at peak hours will be helpful for making the choice of TSP.

2.6.4 Conflicts with Major Delay to Traffic

There are some intersections, like Third and King Street or Embarcadero and Broadway Street, where traffic volume is very high in peak hours. Giving priority to the transit vehicle in these intersections is very difficult. So it is important to analyze these problems before installing TSP. The delays in travel time can make the public angry and can cause more problems.
2.6.5 Near Side Bus Stops

For efficient use of TSP, the bus stops should not be close to intersection. It is best if they can move near side bus stops to the far side, for better results. The bus stop before intersection is called as near side bus stop and after intersection it is called as far side bus stop. If the bus stop can not be moved, TSP may only be implemented with near side stops. But this may be not be more efficient. If the bus stops are far side, then bus delays will be reduced.

2.7 Walk-through Audits

According to James Fitzsimmons (2008) a Walk through Audit is a process oriented survey given to customers and managers to evaluate customer perception of the service experience. A Walk through Audit gives an idea about how the customers view the organization. It’s actually feedback from the customer about the organization’s service, and it provides opportunities for the organization to improve their product. Walk through Audits also improve efficiency by reducing cost, eliminating waste, and utilizing resources. In service industries it is an opportunity to evaluate service from the customer’s point of view. It helps reduce the gap between the expected and the perceived service.

Santa Clara Valley Transportation Authority (VTA) is a good example. They distribute survey forms to riders and collect customer feedback. Any gaps between customer demands and VTA’s services are then minimized.

Figure 4 depicts another example of a Walk through Audit conducted by SFMTA. The campaign was launched to improve the public transportation service along the Van
Ness Street corridor. A common thread from customer’s feedback was that bus travel time was too slow. The customer statements motivated SFMTA senior staff to investigate and implement TSP in San Francisco.

**Figure 4: Customer Survey Form (Source: www.dot.ca.gov)**
2.8 Case Studies

2.8.1 Los Angeles, California

In 2000, the Los Angeles Department of Transportation (LADOT) and the Metropolitan Transportation Authority (MTA), equipped 654 intersections along 9 public transit corridors, served by 283 buses, with Transit Signal Priority. Based on a 1995 study that found that about 24% of bus delay was caused by red lights, the Agency’s goal was to reduce bus travel times by 20-25%. LADOT's transit signal priority system tracks the movement of each Metro Rapid bus and determines its approximate speed via loop detectors embedded in the pavement along the route. Depending on the proximity of a Metro Rapid bus to a signalized intersection, the system will extend green signal time up to 10 seconds or activate a green signal up to 10 seconds earlier to reduce the amount of waiting time at intersections (Metronet.news, 2004).

According to a survey completed by the LADOT and MTA for the U.S. DOT, Transit Signal Priority Handbook (page 114-115), the system is centralized, i.e. the controller communicates to the central system when the bus is approaching. The central system initiates all phase changes. The local controller can only time phases and can be used for backup. Strategies used include early green, green extension and phase hold with most cycles 90 seconds long. The “don’t walk” phase is never shortened. TSP is integrated with the Emergency Medical System’s (EMS) pre-emption at some locations.

According to the Federal Transit Administration, the project is innovative. “The bus signal priority system is based on communications between antenna embedded in the street pavement, radio transmitters mounted underneath the bus, and the LADOT’s
Transit Priority Manager (TPM) computer. Once a bus and location are received by the TPM, the computer determines the need for traffic signal priority. If a bus is ahead of schedule by 50% or greater, then no signal priority is granted. However, if a bus is behind schedule by 50% or greater, then signal priority is. MTA’s Bus Operations Control Center monitors the real-time progress of buses and helps manage bus "bunching" and "gaps" as they progress along the corridor.” (U.S. dot, 2005)

Funding for the project was provided by the MTA capital budget. The cost of project implementation for the 9 lines was over $10 M for design and signal work. Software was the largest expense, followed by transponders and cabinets. Controllers were about $3K each. Overall TSP costs were about $30K per intersection.

2.8.2 Zurich, Switzerland

One of the most famous public transit systems is found in Zurich, Switzerland. Not only does Zurich have one of the highest levels of per capita transit ridership in the world (Nash & Sylvia, 2001), it is one of the most widely documented, due in a large part to transit signal priority. However, it should be noted that TSP is only one of four types of transit improvements that the city of Zurich implemented. The four types of improvements, including TSP, were roadway improvements and traffic regulations, transit system operations, and separate right of way.

TSP was initially instituted in Zurich by allowing transit operators to control traffic signal operation by pushing a button when their vehicle approached a traffic signal to turn the traffic signal green (Nash & Sylvia, 2001, pg 75). This technique did not work basically because the transit driver had too much to focus on besides pushing a
button at a signaled intersection. In addition, when it did work and the transit driver did have time to push the button to turn the light green, traffic flow problems were created. A system that didn’t require operator input and that didn’t create traffic flow problems needed to be designed.

Zurich transit planners made a differentiation between “static” and “dynamic” traffic light systems. Historically they had a traffic signal progression called “static” because it was based on repeating patterns of signal cycles at a series of connected traffic signals (pg. 76). In other words, traffic signals turn green as a lot of vehicles travel through intersections. Then when TSP is implemented in this type of traffic signal progression, the regular traffic pattern is disrupted and traffic flows are impacted.

According to Nash & Sylvia,

“A “dynamic” system is one in which the traffic signal timing is controlled by computer programs based on the geometry of the intersection and on real-time traffic data collected from sensors in the roadway. The sensors communicate traffic volume information to the system’s central computers, where it is combined with data from the rest of the network to determine the most efficient traffic signal operation at all system intersections—in real time. This type of system can be termed a “dynamic” system because it does not rely on a constantly repeating cycle at each intersection.” (Nash & Ronald, 2001)

In a “dynamic” system, TSP has little impact on the flow of traffic because turning the light green or holding it red is a random event. The “dynamic” system has
provided additional capacity and given it to transit vehicles; therefore, private vehicles have not been hurt, but transit has been helped.

For example, suppose a traffic signal is phased to operate so that the eastbound/westbound traffic is first allowed to turn left, then eastbound/westbound traffic is allowed to travel through. Next the northbound/southbound traffic is allowed to turn left, and the northbound/southbound traffic travels through. The intersection’s light signal follows this phase routinely. If the TSP system is on the eastbound/westbound travel through, and the transit vehicle’s indicator picks up that the vehicle will reach the intersection in 30 seconds, regardless of what phase the light is in, the controller will turn the eastbound/westbound travel through green. After the transit vehicle passes through the intersection, the controller determines what the interrupted phase was and returns to that point and continues the phase again. The phasing of the traffic signal changes to provide a green light for public transport exactly when the public transport needs it (Livablestreets.com, 2009).

Finally, since the phasing is random, it does not add additional burden to the normal flow of traffic. However, if automobile drivers are use to a particular signal light pattern, the change to this random phasing may cause problems. In an effort to reduce the driver’s inconvenience, Zurich launched a public service campaign telling the public about its Transit Signal Priority Program.
3 SFMTA VENDOR SURVEY

SFMTA contacted seven companies to solicit their interest in establishing TSP throughout the City of San Francisco for its buses and light rail vehicles. Five vendors responded and each received a SFMTA Vendor Survey. The Vendor Survey requested information on the design requirements listed below, and the compiled Vendor Surveys are tabulated in Appendix B.

- Distance transmission can be read
- Accuracy
- GPS canyons and dead reckoning adjustments
- Latency
- Speed and direction of bus
- Distance to an intersection with encoded intersection identification
- Ability for two-way communication between the intersection and the bus
- Intersection identifier
- Phase status
- Phase timers
- Priority request acknowledgement
- Priority status
- Ability to accept data from the bus’s existing on-board computer
- GPS data
- Bus route number
• Passenger counts

• Schedule

• Check-in/check-out calls

• TSP priority level

• Data format

• Reliability

• Security and encryption of the transmission

• Door contact inputs

• Power consumption

• Ability to use existing equipment on the bus/intersection

• Size of equipment

• Interface with other radio transmission on the bus

• Use of vendor’s equipment on emergency vehicles

• Integration of equipment with San Francisco’s Radio Project

• References
4 DEMONSTRATION TESTING

Five companies successfully demonstrated their equipment using radio-based communications with existing traffic signal software at three intersections on Mission Street in San Francisco. Essential performance features that were met by all vendors included the following:

1. Approaching vehicle transmission 1000 feet from intersection.
2. Accuracy within 20 feet of the vehicle.
3. Latency within 3 seconds.
4. Ability to communicate the route number of the bus.
5. Ability to work in emergency vehicles.
6. Ability to communicate with existing signal software.
7. Security of communications.

Key performance parameters that differed amongst the companies included transmission frequencies, equipment types and sizes, experience with emergency vehicle preemption, automatic vehicle location communication, and cost. Table 2 on the following page lists comparisons of the vendor’s technologies.

Based on the information provided by the vendors during demonstration testing, it became necessary to do further research regarding frequency comparisons since different technologies were transmitting data via 900 MHz, 2.4 GHz, or 4.9 GHz. The Table 3 lists the advantages and disadvantages of each frequency. Based on these factors, 900 MHz frequency appears to be preferred due to its reduced implementation costs, longer
distance capability, and greater reliability. However, 2.4/4.9 GHz can successful utilize the existing AVL/GPS equipment on the bus, and this factor may outweigh others.

Table 2: Preliminary Vendor Comparisons

<table>
<thead>
<tr>
<th>Company</th>
<th>Frequency</th>
<th>Emergency Vehicle Preemption Experience</th>
<th>Additional Antennas on Bus</th>
<th>Equipment on bus</th>
<th>Use of the GPS Feed from the Bus’ AVL System</th>
<th>Communicate All Data From AVL System</th>
<th>Use of the 4.9 GHz Bulk Data Transfer Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMTRAC</td>
<td>900 MHz</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>EVIEWS</td>
<td>900 MHz</td>
<td>Yes</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>GTT</td>
<td>2.4 GHz</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>ITERIS</td>
<td>2.4 GHz</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NOVAX</td>
<td>2.4/4.9 GHz</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 3: Frequency Comparisons

<table>
<thead>
<tr>
<th>900 MHz Frequency</th>
<th>2.4 GHz / 4.9 GHz Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages:</strong></td>
<td><strong>Advantages:</strong></td>
</tr>
<tr>
<td>Efficient Vehicle-to-intersection communication</td>
<td>Ability to transmit data packets (not just vehicle ID/class)</td>
</tr>
<tr>
<td>Potential for vehicle-to-external system</td>
<td>Additional shared applications beyond TSP</td>
</tr>
<tr>
<td>communication</td>
<td></td>
</tr>
<tr>
<td>Reduced implementation costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Spectrum (unlicensed)</td>
<td>Most crowded spectrum due to WiFi</td>
</tr>
<tr>
<td>Longer distance capability</td>
<td>Transmits easily through walls</td>
</tr>
<tr>
<td>Easier to “bend” around obstructions</td>
<td>Heavily impacted by leaves and moisture</td>
</tr>
<tr>
<td>Better reliability</td>
<td>Can use GPS</td>
</tr>
<tr>
<td>900MHz, 1W radio power plus 6dB gain</td>
<td>2.4GHz, 1W radio power plus 6dB gain</td>
</tr>
<tr>
<td>Antennas = 15 - 25 miles</td>
<td>Antenna = 5 - 15 miles</td>
</tr>
<tr>
<td>900MHz, 100mW radio power plus 16dB</td>
<td>2.4GHz, 100mW radio power plus 16dB</td>
</tr>
<tr>
<td><strong>Disadvantages:</strong></td>
<td><strong>Disadvantages:</strong></td>
</tr>
<tr>
<td>Early products remain proprietary in nature</td>
<td>Requires coordination with IT staff</td>
</tr>
<tr>
<td>Limited two-way communication is provided</td>
<td>Municipal WiFi experience has been challenging</td>
</tr>
<tr>
<td></td>
<td>Higher costs</td>
</tr>
</tbody>
</table>

Another characteristic that required further research involved the type of networks that the vendor’s equipment used, specifically called “Mesh Networks” versus “Point-to-Point Bridge Networks”. Table 4 below lists the advantages and disadvantages of each network. Based on these factors, point to point bridge networks would be preferred due to lower costs, less on-board equipment, and the overall simplicity of the network.
Table 4: Mesh v/s Point-to-Point Bridge Networks

<table>
<thead>
<tr>
<th>MESH NETWORK</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One equipment on Bus and one on the traffic light is needed which will add the installation cost. Maintenance costs will be high. No traffic problem because there are dedicated links. Robust as failure of one link does not affect the entire system. Security as data travels along a dedicated line. Point to point links make fault identification easy.</td>
<td>The hardware is expansive as there is dedicated link for any two nodes. Mesh wiring which can be difficult to manage. Installation is complex as each node is connected to every node. Routers are required at every intersection.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POINT TO POINT BRIDGE NETWORK</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No additional on-bus equipment is required - reducing equipment, installation, and on-going maintenance costs while minimizing antenna clutter on the transit vehicles. Failure of one link will take the network down. Security as data travels along a dedicated line. Points to point links make fault identification easy.</td>
<td>Can't use the GSP system on bus. No WiFi for the riders. No back up battery in case of power shut off.</td>
</tr>
</tbody>
</table>
5 DECISION MATRIX ANALYSIS

Decision Matrix Analysis (DMA) is a common tool used in management to compare alternative system technologies and determine which proposed option best meets project specifications. The Decision Matrix provides an effective way to assess multiple variables (such as cost, environmental impact, etc.) across competing alternative technologies, utilizing a weighted ranking comparison system. A Decision Matrix is basically an array with two axes. One axis lists the proposed alternatives under consideration. The other axis lists the relevant criteria or factors being evaluated – with each variable weighted according to its respective importance.

5.1 Building the Matrix for TSP

Five companies responded to SFMTA’s RFI with proposed TSP systems. These five systems will be compared utilizing a Decision Matrix, in order to ascertain which system best serves SFMTA’s multiple and overarching objectives for the project.

To apply DMA to San Francisco’s TSP Project, the following steps will be taken:

1. (a) The five proposed design alternatives (or TSP systems) are listed on the horizontal axis. Each company or system is assigned a column of the matrix.

(b) Eight design criteria (elaborated below), as identified by the SFMTA Project Team, are listed along the vertical axis of the matrix.

2. The relative importance of each design criteria is determined by mutual consensus of the Project Team by assigning numbers 0 to 4, where 0 is absolutely unimportant, 1 is unimportant, 2 is neither unimportant or important, 3 is important and 4 is very
important. Note that these ratings are not mutually exclusive and different criteria
 can have the same relative importance.

3. By working down the columns of the matrix, each system is scored for each criterion
 utilizing the scale of 0 to 4. Again note that different options do not have to have
different scores. For example, if none of them are important, then all options would
score 0.

4. Each score in step 3 is multiplied by the Relative Importance Values calculated in
step 2, resulting in weighted scores for each TSP System-Design Criteria
combination.

5. To determine which proposed TSP system best meets the scope of project
specifications, the weighted scores for each variable are added. Assuming the
matrix is adequately designed, and the comparison criteria accurately
identified and rated, the TSP system with the highest total combined weighted
value should be selected as the system that best meets SFMTA’s overarching
project specifications

(http://www.mindtools.com/pages/article/newTED_03.htm).

5.2 Design Criteria

Based on the vendor survey, eight design criteria were identified. These include
cost, frequency, emergency vehicle preemption experience, antennae and equipment on
buses, communication from the bus’ AVL systems, GPS feed and 4.9 GHz bulk data
transfer. Each is described below.
• **Cost**

The overall system cost is an important consideration since the first year program allocation is $3 million. This amount will pay for the engineering, equipment on the buses and the intersections, installation and labor, and any software costs.

• **Frequency**

Different TSP technologies transmit data via various radio frequencies including 900 MHz, 2.4 GHz, and 4.9 GHz. As mentioned previously, the 900 MHz frequency range appears to be preferred due to its reduced implementation costs, longer distance capability, and greater reliability. However, 2.4/4.9 GHz can successfully utilize the existing AVL/GPS equipment on the bus, and this aspect may outweigh the advantages of the 900 MHz system.

• **Emergency Vehicle Preemption Experience**

Currently, SFMTA has emergency vehicle preemption on its fire trucks and ambulances. Preemption refers to the transfer of the normal control (operation) of traffic signals to a special signal control mode for the purpose of servicing emergency vehicle passage (U.S. DOT, 2005). Any company that had experience in this area would be preferred for compatibility with existing systems.

• **Additional Antennas on Bus**

Every SFMTA bus is equipped with two antennas: one for the Global Positioning System (GPS) and the other antenna for 802.11 wireless local area network (WLAN) communication over 2.4, 3.6, and 5 GHz frequency bands. SFMTA would prefer not to install additional antennas.
• Equipment on Bus

There is a plethora of equipment on the buses, and SFMTA’s concern over adding more equipment is warranted. First, additional equipment on buses takes up vital space in an already crowded driver’s cockpit. Secondly, the more equipment involved, the more maintenance required. Physical space and costs are two variables that can make a particular technology less attractive.

• Communicate all Data from Automatic Vehicle Location (AVL) System

SFMTA’s buses are equipped with an AVL system that basically determines the location of its transit vehicles. AVL applications include schedule adherence monitoring, operational control and incident management through computer-assisted dispatching (U.S. DOT, 2005). The ability of the TSP system to communicate all data from the AVL system is considered a benefit.

• Use of the Global Positioning System (GPS) Feed from the Bus’ AVL

The AVL systems on SFMTA’s transit vehicles now use the global positioning system (GPS) to determine vehicle location. Use of the existing GPS is another benefit.

• Use of the 4.9 GHz Bulk Data Transfer Radio

The buses are currently equipped with a 4.9 GHz radio and it would be beneficial if the TSP system could utilize it.

5.3 The TSP Decision Matrix Analysis

Table 5 on the following page shows the draft TSP Decision Matrix. As of the writing of this progress report (March 12, 2010), the Project Team has not yet formally
met to weigh and measure the design criteria per vendor. The numbers shown in the matrix represent an example of how the matrix works. For instance, weights are assigned to the eight factors such that cost, emergency vehicle preemption, use of GPS feed from the bus’ AVL, and communication from the AVL are the most important factors. These are assigned value of 4. The value of 3 is assigned to important criteria including frequency and use of the 4.9 GHz bulk data transfer radio. Neither unimportant nor important is the additional equipment on the bus including additional antennas, and these are assigned a value of 2.

As an example, Iteris is assigned 0-4 ratings based on its conformance to the design criteria. As can be seen from the matrix, Iteris is given a rating of 4 for five of the criteria including cost, frequency, equipment on bus, use of GPS feed, and communication from AVL system. Of importance was the use of the 4.9 GHz bulk data transfer radio. A 2 was assigned to emergency vehicle preemption and additional antenna on the bus. Iteris’ ratings total 27 points, but its score is 48, based on the criteria weights. Similarly, the other companies would be rated and scored to determine the highest scoring alternative. The vendor with the highest score is selected to have the preferred equipment.
## Table 5: TSP Decision Matrix

<table>
<thead>
<tr>
<th>CRITERIA:</th>
<th>WEIGHT:</th>
<th>EMIRAC</th>
<th>E-MEWS</th>
<th>GTT</th>
<th>ITERIS</th>
<th>NOVAX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
</tr>
<tr>
<td>COST</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>4</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>EQUIPMENT ON BUS</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>EMERGENCY VEHICLE PREEMPTION</td>
<td>4</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>COMMUNICATE ALL DATA FROM AVL SYSTEM</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>REFERENCES/EXPERIENCE</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ADDITIONAL FEATURES</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>25</td>
<td>14</td>
<td>52</td>
<td>20</td>
<td>72</td>
<td>9</td>
</tr>
</tbody>
</table>
RIST ANALYSIS MATRIX AND EXPECTED VALUE

Decision making involves risk, and the minimization of risk during the project’s life cycle is warranted for a successful outcome. There are four steps involved in risk analysis:

- Identification of the risk.
- The probability of the risk occurring.
- The impact or severity of the risk should it occur.
- Steps to be taken to address the risk.

The first step is to identify potential risks. According to Hunt (2004), these may be related to internal organizational risks, project management risks, technological risks, non-recurring risks, and legal risks. For the purpose of this paper, technological risks are addressed, and they are listed in Table 6 below.

**Table 6: TSP Technological Risks**

<table>
<thead>
<tr>
<th>Risk</th>
<th>Statement of Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>The cost of the system exceeds the project’s budget.</td>
</tr>
<tr>
<td>Frequency</td>
<td>The system’s operating frequency is at a low bandwidth, causing interference with the signal.</td>
</tr>
<tr>
<td>Equipment on Bus</td>
<td>The on-board equipment is of substandard design, materials, and/or workmanship.</td>
</tr>
<tr>
<td>Emergency Vehicle Preemption</td>
<td>The preemption control that requires terminating normal traffic control to provide the emergency vehicle needs does not exist as part of the system.</td>
</tr>
<tr>
<td>Communicate All Data From the AVL System</td>
<td>The TSP system is unable to communicate all of the data required from the existing AVL.</td>
</tr>
<tr>
<td>References &amp; Experience</td>
<td>The system provider does not have adequate experience implementing TSP in other jurisdictions.</td>
</tr>
<tr>
<td>Additional Features</td>
<td>The TSP system is incapable of providing on-board internet service for passengers.</td>
</tr>
</tbody>
</table>
The next step is to evaluate the possibility that the risk will occur and the possible effect on the success of the project (Hunt, pg. 136). This is often referred to as Expected Value (EV), and it is a way to measure the relative merits of decision alternatives.

According to Olivas (2007), the EV term is a mathematical combination of the probability of a risk occurring and the impact if it occurs. Babcock and Morse (2007) state that given the future states of nature and their probabilities, the solution in decision making under risk is the alternative $A_i$ that provides the highest expected value $EV_i$, which is defined as the sum of the products of each outcome $O_{ij}$ times the probability $p_j$ that the associated state of nature $N_j$ occurs such that:

$$ EV_i = \sum_{j=1}^{n} (p_jO_{ij}) $$

In this case, the goal of the EV calculation is to find the alternative with the lowest EV as the best choice since we want the alternative with the least amount of risk.

Table 7 on the following page is a risk analysis matrix that calculates the EV of each alternative. Each design criteria is assigned a probability of occurrence. These probabilities are subjectively assigned by the project team leaders depending on their preferences and values and are normalized to 1 (Modarres, 2006). The alternative is then rated in the range of 5 (high) and 0 (low) depending on the impact of the risk on the

<table>
<thead>
<tr>
<th>Quality</th>
<th>The vendor’s technology has an inadequate quality assurance program.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4 Compatibility</td>
<td>The TSP system has inadequate architectural design</td>
</tr>
<tr>
<td>Technological Competence</td>
<td>The TSP system is beyond the team’s technological competence.</td>
</tr>
</tbody>
</table>
project. The EV is then calculated by multiplying the probability by the impact and the products totaled.

**Table 7: Risk Analysis Matrix (Expected Value)**

<table>
<thead>
<tr>
<th>Risk Analysis Matrix</th>
<th>EMTRAC Impact</th>
<th>EMTRAC EV</th>
<th>E-VIEWS Impact</th>
<th>E-VIEWS EV</th>
<th>GTT Impact</th>
<th>GTT EV</th>
<th>ITERIS Impact</th>
<th>ITERIS EV</th>
<th>NOVAX Impact</th>
<th>NOVAX EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST</td>
<td>0.20</td>
<td>3</td>
<td>0.6</td>
<td>1</td>
<td>0.2</td>
<td>2</td>
<td>0.4</td>
<td>1</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>0.10</td>
<td>2</td>
<td>0.2</td>
<td>2</td>
<td>0.2</td>
<td>1</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EQUIPMENT ON BUS</td>
<td>0.05</td>
<td>2</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>EMERGENCY VEHICLE PREEMPTION</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.15</td>
<td>4</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>COMMUNICATE ALL DATA FROM AVL SYSTEM</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>REFERENCES/EXPERIENCE</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>4</td>
<td>0.2</td>
<td>1</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>ADDITIONAL FEATURES</td>
<td>0.05</td>
<td>2</td>
<td>0.1</td>
<td>2</td>
<td>0.1</td>
<td>2</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QUALITY</td>
<td>0.15</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
</tr>
<tr>
<td>D4 COMPATIBILITY</td>
<td>0.10</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>TECHNOLOGICAL COMPETENCE</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>2</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.00</td>
<td>17</td>
<td>1.90</td>
<td>15</td>
<td>1.55</td>
<td>18</td>
<td>1.85</td>
<td>17</td>
<td>1.90</td>
<td>12</td>
</tr>
</tbody>
</table>
7 ECONOMIC JUSTIFICATION

In order to support moving forward with a pilot test project utilizing TSP, a preliminary economic justification for project implementation has been conducted. According to Fleck (2007) TSP for the SFMTA can be justified based on three economic cost analyses:

- The benefit cost ratio
- The net present value
- Return on Investment

First consider the simple benefit/cost (B/C) ratio whereby:

$$\frac{\sum \text{Total Benefits}}{\sum \text{Total Costs}} = \text{BC Ratio}$$

Basically, the benefits include the savings for passenger travel time, the cost of bus operations per intersection, and the cost of system implementation.

Therefore,

$$\text{BC Ratio} = \frac{\sum (\text{Cost savings of passenger travel time} + \text{Cost savings of bus operations})}{\sum \text{Cost of TSP Implementation}}$$

Several assumptions were made in order to determine the BC Ratio, including number of buses per hour, number of passengers, the value of passenger’s time, and bus hours of operation. For initial analysis, the assumptions are as follows:

- Five (5) buses per hour in each direction = ten (10) buses per hour.
- Buses operate twenty (20) hours per day, six (6) days per week, fifty-two (52) weeks per year.
- Cost of operation is approximately $132 per hour.
• The average number of passengers per bus is approximately twenty (20).
• The value of passenger’s time equals ten dollars ($10) per hour.
• The average time saved due to implementation of TSP per intersection is three (3) seconds.

To calculate the B/C ratio, if the benefits to passengers is determined to a savings of three seconds time per intersection, then

\[
3 \text{ seconds/bus} \times 10 \text{ buses/hour} \times 20 \text{ hours/day} \times 10/\text{hour} \times 20 \text{ passengers/bus} \\
\times 6 \text{ days/week} \times 52 \text{ weeks/year} / 3600 \text{ seconds/hour} = \$10,400/\text{year}.
\]

Next, calculate the benefits to the City for operations such that:

\[
3 \text{ seconds/bus} \times 10 \text{ buses/hour} \times 20 \text{ hours/day} \times 132/\text{hour} \times 6 \text{ days/week} \times 52 \text{ weeks/year} / 3600 \text{ seconds/hour} = \$6,865/\text{year}.
\]

The total benefits per intersection of TSP would be:

\[
\$10,400 + \$6,865 = \$17,265 \text{ per year}.
\]

The cost of TSP is calculated by taking the full program cost of $1.73 M and dividing it by the number of installed intersections, estimated at 50, resulting in an estimated cost of $34,600 per intersection. As a check, Fleck (2007) estimated that the implementation cost would consist of the following:

\[
\begin{align*}
\text{Material costs} &= \$5,000 \\
\text{Labor costs} &= \$21,000 \\
\text{Controller costs} &= \$6,000 \\
\text{Contingency} &= \$2,000 \\
&= \$34,600
\end{align*}
\]

If the program is financed over a ten-year period and at 6% interest, the annual cost per year is $4,785 per year. Therefore,
B/C Ratio = $17,265 / $4,785 = 3.6.

Figure 5 illustrates the project’s B/C Ratio—the steeper the slope, the higher the ratio of benefits to cost. As a general rule, a project with a B/C Ratio greater than 2 is considered justified (Bowman, 2003).

![Figure 5: Benefit to cost ratio](image)

The B/C Ratio can also be evaluated by considering the benefits individually, i.e. the B/C Ratio to SFMTA and the B/C Ratio to the riders. In this case, the B/C Ratio for SFMTA is approximately

$$\text{B/C Ratio} = \frac{6,865}{4,785} = 1.4$$

And the B/C Ratio for the riders is approximately

$$\text{B/C Ratio} = \frac{10,400}{4,785} = 2.2.$$  

Therefore, to implement TSP, it is more beneficial to public transit riders than it is to SFMTA Operations.

Net present value (NPV) is another useful gauge of project justification, since alternatives are not considered. To calculate the NPV, the total discounted costs are subtracted from the total discounted benefits. For SFMTA TSP,

$$\text{NPV} = 17,265 - 4,785 = 12,480$$
In general, projects with positive net benefits should be considered; the greater the net benefits, the more justifiable the project.

(www.dot.ca.gov/hq/tpp/offices/ote/benefit_cost/calculations/types.html).

Finally, the return on investment (ROI) can be calculated as:

\[
ROI = \frac{\text{Gain from Investment} - \text{Cost of Investment}}{\text{Cost of Investment}}
\]

Here the gain on investment is represented by the total benefits calculated above which equaled $17,265. The cost of investment can be determined from the estimated cost of the program at $1.73M. If $1.73M is invested to install and operate 50 intersections over the next 10 years, the program would cost $34,600 per year. If $34,600 is considered a present value, the amortized value would be given by:

\[
A = P \left(\frac{A}{P}, 10 \text{ years}, 6\%\right) = $34,600 (0.1359) = $4,700 \text{ per year.}
\]

Therefore, the ROI would be given by:

\[
ROI = \frac{($17,265 - $4,700)}{$4,700} = 2.7 \text{ years.}
\]

In other words, according to the above calculations, the TSP program is expected to pay for itself in approximately 2.7 years.

The ROI per year can be calculated as followed:

The total investment cost is $1,730,000.

The Total benefits after investment cost per year = $628,250.

\[
\%\text{ROI per year} = \left(\frac{\text{Gain from Investment}}{\text{Total amount of Investment}}\right) \times 100
\]

\[
= \left(\frac{628250}{1730000}\right) \times 100
\]

\[
= 36.3\%
\]

Thus, the ROI on investment per year would be 36.3%.
8 CONCLUSION

TSP is an operational strategy used to manage traffic and facilitate the movement of public transit vehicles through traffic-signal controlled intersections (U.S. DOT, 2005). Essentially, TSP senses oncoming public transit vehicles, and either turns the traffic light green or holds the traffic red light in order to improve transit performance. Types of TSP include passive and active, and detection techniques include zone, point, and continuous detection.

This project investigates various Transit Signal Priority (TSP) systems for the San Francisco Municipal Transportation Agency (SFMTA). In order to do so, TSP is defined according to the Department of Transportation’s (DOT) TSP Handbook (2005). The research conducted highlights the benefits of public transportation and reviews case studies in Los Angeles, California and Zurich, Switzerland.

In response to a Request for Information (RFI), five companies completed a survey describing their technologies. The vendors also participated in demonstration tests that validated the effectiveness of their equipment. Based on the data collected in the surveys and during testing, seven design criteria were rated. These included the following:

1. Cost.
2. Frequency.
3. Equipment on Bus.
5. Communication from existing AVL System.
Applying decision matrix analysis, the companies were also rated according to their ability to meet the criteria. The preferred technology is the company that has the highest score. As a result of the decision matrix Analysis, Novax has the highest performance score (76) and lowest risk rating (1.55); however the final decision will be made by the radio project vendor. Also, some other criteria such as being locked into a proprietary system are also being discussed.

Finally, three methods taught in modern engineering cost analysis were used to justify the TSP Program for the SFMTA—benefit cost (B/C) analysis, net present value (NPV), and the return on investment (ROI). All three methods proved that the Program should have a positive financial impact for the SFMTA. In particular, the overall B/C ratio was 3.6, the NPV was valued at over $12.5K, and the project would pay for itself in approximately 2.7 years. Therefore, the TSP Project is economically justifiable.
9  FURTHER STUDY

Further study is recommended to confirm that TSP, once implemented for SFMTA, can save riders approximately 10 percent travel time. The demonstration tests conducted in this study, although successful in asserting performance, did not compare or calculate decreased travel times of the bus travelling on Mission Street in San Francisco. One method to do this would be to first physically record the time elapsed for a non-TSP equipped bus to travel through a certain number of intersections. Next, record the time it takes a TSP equipped vehicle to travel through the same intersections. Comparing those times would provide confirmation of the economic assumption that there is a savings time of three seconds per intersection. SFMTA needs to do more research to quantify the savings realized for TSP enabled systems.

Secondly, although there is an enormous effort underway by SFMTA towards constructing TSP, it is important to use a systematic approach from the planning stage through the implementation process. This study has provided documentation regarding some of the important planning and design steps undertaken by SFMTA thus far. Further study should address the recommended systems engineering approach outlined in the TSP Handbook (DOT, 2005), pages 9 – 40. In particular, the following steps should be thoroughly undertaken:

- TSP project implementation including procurement, installation and verification/validation.
- Operations and maintenance, including ongoing performance monitoring, management, and procedures to ensure that the system is operating.
Evaluation, verification, validation and building on TSP, including an evaluation study, ongoing data collection, and building on TSP benefits through transit scheduling.

Finally, the “Implementation of Zurich’s Transit Priority Program” (Nash & Sylvia, 2001) is recommended for further study specifically since TSP was only one of four types of transit improvements that the city of Zurich implemented. The four types of improvements, including TSP, were roadway improvements and traffic regulations, transit system operations, and separate right of way. This fact suggests that other transit policies may enhance a TSP program.
REFERENCES


Babcock, Daniel L. and Morse, Lucy C.  (2007). Managing Engineering and Technology, pg. 84.


## APPENDIX A: PROJECT SCHEDULE

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal Draft</td>
<td>10/9/2020</td>
<td>10/13/2020</td>
</tr>
<tr>
<td>Research Scope, Prepare Paper and Presentation</td>
<td>10/29/2020</td>
<td>10/30/2020</td>
</tr>
<tr>
<td>Preliminary Project Scope Proposal</td>
<td>11/1/2020</td>
<td>11/2/2020</td>
</tr>
<tr>
<td>Literature Search Proposal</td>
<td>11/5/2020</td>
<td>11/6/2020</td>
</tr>
<tr>
<td>Research Economic Justification, Prepare Paper and Presentation</td>
<td>11/7/2020</td>
<td>11/8/2020</td>
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<tr>
<td>Economic Analysis Presentation</td>
<td>11/9/2020</td>
<td>11/10/2020</td>
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<tr>
<td>Prepare Final Paper</td>
<td>11/11/2020</td>
<td>11/12/2020</td>
</tr>
<tr>
<td>Final Project Scope Plan Day</td>
<td>11/13/2020</td>
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<td>Final Project Plan Day</td>
<td>11/15/2020</td>
<td>11/16/2020</td>
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<tr>
<td>Final Presentation</td>
<td>11/17/2020</td>
<td>11/18/2020</td>
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<tr>
<td>Technical Meeting (Sloan Engineering)</td>
<td>11/19/2020</td>
<td>11/20/2020</td>
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<tr>
<td>System Test Use and Signals</td>
<td>11/21/2020</td>
<td>11/22/2020</td>
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<tr>
<td>Demonstration Tasks</td>
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<td>11/24/2020</td>
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<tr>
<td>Schedule of PelVIC TBP System</td>
<td>11/27/2020</td>
<td>11/28/2020</td>
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<td>12/31/2020</td>
<td>1/1/2021</td>
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Note: Dates are in the format MM/DD/YY.
## APPENDIX B: COMBINED VENDOR SURVEYS

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<tr>
<th>ITEM</th>
<th>Design Feature</th>
<th>GTT</th>
<th>ITERIS</th>
<th>ACS</th>
<th>NOVAX</th>
<th>EMTRAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance transmission can be read</td>
<td>The radio has a range of at least 2500 ft. If there are no obstructions, and the radio is mounted high, this distance will likely be exceeded. If it is mounted low and/or there are physical obstructions that will be reduced. Obstructions generally cause more intermittent operation. The lost signal/hold time may be extended in these instances.</td>
<td>Communications between transit vehicles and the intersection controllers are done using an IEEE 802.11 b/g compliant wireless local area network (WLAN). Transit vehicles can communicate with intersections from anywhere on the wireless network which can be as far as a few miles although, more typically, is less than 1,200 ft depending on the requirements of the controller software and its timing. Communications are not limited by the line of sight between the transit and the controller.</td>
<td>A network connection can be established approximately 1000 ft out or more from the intersection depending on conditions, however, ACS would not likely send the actual request or priority until about 600 ft away (about 20 seconds away).</td>
<td>With the proposed mesh wireless architecture; there is literally no limit to the distance over which data transmission can be read.</td>
<td>Typically 3000 ft but can be extended to greater than 4000 ft through the use of different antennas. For our testing on the pilot, the zones were setup for about 1500 ft.</td>
</tr>
<tr>
<td>2</td>
<td><strong>Accuracy</strong></td>
<td>Our WAAS enable GPS receiver has an accuracy of +/-5 meters.</td>
<td>Accuracy related to transit vehicle positioning is dependent on the on-board GPS system. The proposed TSP system utilizes the AVL systems that are part of the on-board transit operations management system. Both ACS OrBCAD and Continental TransitMaster systems currently support the proposed TSP solution. Typically, GPS systems provide for positioning accuracy of about 20 feet or less 95 percent of the time.</td>
<td>No Answer</td>
<td>10 feet CEP at 20 MPH.</td>
<td>100% as dictated by the virtual zones. The zones utilized during the pilot testing encompassed more than one intersection at a time.</td>
</tr>
<tr>
<td>3</td>
<td><strong>GPS canyons and dead reckoning adjustments:</strong></td>
<td>Accuracy with regard to predicting arrival times at signalized intersections depend on a variety of factors and cannot be easily quantified. Currently, the messaging protocol allows for a position update message as the transit vehicle approaches the intersections which can be used for improved accuracy if supported by the controller firmware.</td>
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<td>Our intersection position is averaged over several days so the position will not drift. Since our GPS receivers have very good sensitivity we do not have a need for eternal connections.</td>
<td>The proposed approach for TSP deployment is based on using the on-board transit operations management and communications systems. Both the ACS OrbCAD and ACS uses GPS as a primary source with odometer as a backup for dead reckoning in areas where GPS is not available. Use of a Gyro to enhance this solution is available as an option.</td>
<td>In a GPS canyon, GPS manufactured by Novax enhances GPS locations by dead reckoning (via odometer and gyro input). In the case where an AVL vendor's GPS is used, availability of the positioning in use for the pilot test utilized GPS, Dead Reckoning, and on-board Map Matching. The test route in use during the pilot didn't really present a difficult challenge for the</td>
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</table>
Continental TransitMaster systems currently support the proposed TSP approach. Both of these transit operations management systems offer advanced and proven AVL capabilities for maintaining vehicle positioning data in GPS canyons using dead reckoning adjustments. GPS augmentation depends on the particular vendor's equipment design. Trapeze hardware, we chose to test in the downtown urban canons. The maps of this route are included in the presentation.

| 4 | Latency: | There is a 3 second latency in the transmission time between the vehicle and the intersection. But since this is a known value, the latency is factored in when the intersection is calculating the ETA and distance of the approaching messages sent from transit vehicles to intersection controllers over the WLAN is less than one second under all normal operating conditions. | WLAN transmissions typically range from 40ms to 100ms. | Typically in-vehicle equipment transmits information to intersection equipment in less than 50 ms. | Its takes 1 to 1.5 secs to synchronize to an intersection once entering a zone. The zone length is extended to compensate for this synchronization time. |
| 5 | **Speed and direction of bus:** | As the bus travels down the road, it’s speed, heading, and location is transmitted once per second. The intersection equipment then calculates the ETA and distance of the vehicle. ETA and distance thresholds are then programmed into the intersection equipment and used to tell the equipment when to request priority. | The speed and direction traveled of the transit vehicle is determined by the on-bus systems. Currently, the vehicle-to-intersection messaging protocol supported by the ACS OrbCAD and Continental TransitMaster transit operations management system includes vehicle direction and estimated number of seconds until arrival at the intersection where priority is being requested. | Speed and direction of the bus: ACS monitors both of these items and can provide it to the intersection if supported. | In-Vehicle equipment transmits speed and direction of the bus among other data to the intersection equipment. |
| 6 | **Distance to an intersection with encoded intersection** | Our vehicle equipment does not need to know the intersection it is | The distance to the intersection is determined by the on-bus systems. | Distance to an intersection with encoded intersection | The distance the mobile equipment starts talking with the intersection is | Please see the EmTrac standard report included in the presentation |
| 7 | Ability for two-way communication between the intersection and the bus as well as other intersections; i.e. can the equipment on the intersection relay priority requests to adjacent intersections when the vehicle turn signal is activated. This will relay the request to that intersection when and only when communications between transit vehicles and intersections utilize UDP protocol. Communications between the intersection controllers and transit vehicles, are defined by the configured zones. Each intersection is assigned a unique identifier. | Intersections can relay priority requests to adjacent intersections when the vehicle turn signal is activated. This will relay the request to that intersection when and only when communications between transit vehicles and intersections utilize UDP protocol. Communications between the intersection controllers and transit vehicles, | Ability for two-way communication between the intersection and the bus as well as other intersections, i.e. can the equipment on the intersections broadcast priority calls/signal status. | Two-way communication is supported between any intersection to any intersection, any intersection to any bus, and any bus to any intersection. This is a direct benefit of two-way communication. The intersections also communicate with each other. In our testing, 9th talked with 10th and 10th talked with 9th. |}

Identification: The intelligence of when to activate the output resides in intersection equipment. The intersection calculates the distance and ETA of the approaching vehicle. Currently, the bus-to-intersection messaging protocol supported by the ACS OrbCAD and Continental TransitMaster systems includes the estimated number of seconds until arrival at the intersection where priority is being requested. Distance to the intersection where priority is being requested is not provided using the current vehicle-to-intersection message protocol. Identification: Typical checks in boxes are set out about 600ft (centered) from the intersection. A repeated confirmed request for check in occurs 5 seconds after the initial request is sent with encoded intersection identification.
| **intersections broadcast priority calls/signal status downstream to other intersections and/or back to the bus?** | needed. It does not need to relay requests forward since the next downstream intersection is operating independently and will activate the output when its range parameters are met. except at the system level as required to support the UDP messaging, are not supported. TSP messages initiated by transit vehicles may be easily routed to downstream intersections over the WLAN, if supported by the D4 software (which we understand does support forwarding TSP messages to downstream intersections). downstream to other intersections and/or back to the bus? This depends on the equipment used at the intersection. ACS does not currently collect this data. | the proposed mesh wireless network architecture. | 11th. |

| **7.1 Intersection identifier:** | Each intersection broadcasts its name. This is for identification purposes only. The approaching vehicle does not need to know what intersection it is approaching. Signalized intersections where priority will be granted for transit vehicles are provided with unique City code and intersection identifiers as well as intersection-specific IP addresses. The Ability for two-way communication between the intersection and the bus as well as other intersections, i.e. can the equipment on the intersections broadcast priority calls/signal status downstream to other intersections | Intersection identifier is among the two-way data that can be exchanged between any equipment on the mesh wireless network regardless of its type (e.g. bus, intersection) and physical location. | Standard for EmTrac |
Intersection IP address will be the controller IP address, if communications to the controller are via an ethernet port (as would be expected with Type 2070 controllers), or the terminal server IP address if communications with the controller need to be serial. Currently, the bus-to-intersection messaging protocol supported by the ACS OrbCAD and Continental TransitMaster systems includes intersection identification data. and/or back to the bus? This depends on the equipment used at the intersection. ACS does not currently collect this data.

| 7.2   | **Phase status:** | We can monitor and record the status of the greens during each TSP and preemption request. | Phase status data might be sent from the controller to the transit vehicle requesting priority or to downstream ability for two-way communication between the intersection and the bus as well as other intersections, i.e. Phase status is among the two-way data that can be exchanged between any equipment on the mesh wireless | This information can be communicated between the intersections. |
intersections in order to assist in determining whether to initiate priority at downstream intersections. If the D4 software supports the use of the phase status data for downstream intersections, it is recommended that the data be sent using the WLAN from controller to controller. Sending this data from controller to controller would be much more efficient. There is no reason for phase status data to be routed back to the transit vehicle and, as noted above, communications between the intersection can the equipment on the intersections broadcast priority calls/signal status downstream to other intersections and/or back to the bus? This depends on the equipment used at the intersection. ACS does not currently collect this data. network regardless of its type (e.g. bus, intersection) and physical location.
<p>| 7.3 | <strong>Phase timers:</strong> | We will activate our output when the bus reaches its user programmed threshold. The EVP/TSP algorithms of the controller then take over to cycle to the requested green. | See response to question 7.2. | Ability for two-way communication between the intersection and the bus as well as other intersections, i.e. can the equipment on the intersections broadcast priority calls/signal status downstream to other intersections and/or back to the bus? This depends on the equipment used at the intersection. ACS does not currently collect this data. | Phase timers are among the two-way data that can be exchanged between any equipment on the mesh wireless network regardless of its type (e.g. bus, intersection) and physical location. | This information can be communicated between the intersections. |
| 7.4 | <strong>Priority request acknowledgement:</strong> | We have found that most customer prefer to keep their drivers attention focused on the road. Therefore our request acknowledgment is via confirmation. | The priority request is acknowledged to the Central TSP Monitor Tool provided as part of the proposed TSP system as well as to the Central Traffic Management. | Yes | Priority request acknowledgement is among the two-way data that can be exchanged between any equipment on the mesh wireless network regardless of its type (e.g. bus, intersection) and physical location. | This is included in the standard EmTrac log file. |</p>
<table>
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</thead>
<tbody>
<tr>
<td></td>
<td><strong>light installed near the signal heads.</strong></td>
<td><strong>System (MIST), as supported by the D4 software and MIST. The priority request is not acknowledged from the intersection controller to the transit vehicle.</strong></td>
<td><strong>of its type (e.g. bus, intersection) and physical location.</strong></td>
</tr>
<tr>
<td><strong>7.5</strong></td>
<td><strong>Priority status:</strong></td>
<td>A high priority/Emergency vehicle priority request will override a low priority/transit vehicle priority request.</td>
<td>See response to question 7.4.</td>
</tr>
<tr>
<td></td>
<td><strong>Ability to accept and transmit the following data</strong></td>
<td>Our vehicle equipment has J1708 compliant</td>
<td>The proposed approach for TSP deployment is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ability to accept and transmit the following data from</td>
<td>All of the following data can be accepted from the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The AVL system normally transmits its own data.</td>
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<tr>
<td><strong>This is identified in the intersection log files. The EmTrac equipment can currently handle up to 15 different types of priority.</strong></td>
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</tbody>
</table>
from MUNI's on-board computer through the proposed Mobile Data Terminal single point logon and Automatic Vehicle Location (AVL) equipment that will be installed as part of the radio replacement project:

| COM port. We have worked with most AVL providers to establish a COM link between your AVL equipment and our vehicle equipment. The AVL equipment can then talk to our vehicle equipment for conditional priority and other communications between the two devices. | based on using on-board transit operations management and communications systems. Both the ACS OrbcAD and Continental TransitMaster systems currently support the proposed TSP approach. Both the ACS OrbcAD and Continental TransitMaster on-bus systems can be configured to interface with the Muni on-board computer to obtain the data items listed below but we are not able to provide details regarding the desired interface. | Muni's on board computer through the proposed Mobile Data Terminal single point logon and Automatic Vehicle Location (AVL) equipment that will be installed as part of the radio replacement project: | on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. | Transmitting twice may result in twice as much data to store long term |

| **8.1** | **GPS data:** | We can output GPS data in the intersection in the NMEA format to | See response to question 8. | Yes | All of the following data can be accepted from the on board computer / | Both the AVL and EmTrac system have on-board GPS systems. This |
any device in the cabinet such as a controller. We can also drive an output a user defined time for the use in resetting controller clocks. We can also provide GPS data in the vehicle in NMEA format and as part of the J1708 message.

AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. provides a redundant system that backs up the other in

| 8.2 | **Bus route number (including route pattern):** | Via the J1708 interface your AVL system can program the vehicle equipment to transmit the bus route number. See response to question 8. | Yes | All of the following data can be accepted from the on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. The AVL system can pass this information to the EmTrac TSP system |
| 8.3 | **Passenger counts:** | We will look to the AVL device to monitor passenger counts. See response to question 8. | Yes (assuming vehicles are APC equipped) | All of the following data can be accepted from the on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. This information is normally passed by the AVL system in order to preserve intersection bandwidth |
| 8.4 | **Schedule:** | With the J1708 connection to your AVL system we can provide conditional priority based on the schedule adherence capabilities of your AVL system. The AVL system will then activate our equipment to request TSP. | See response to question 8. | Yes, if this refers to Route and Schedule Adherence (RSA) status in terms of early or late. | All of the following data can be accepted from the on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. | The AVL system normally carries the schedule and triggers the TSP system |
| 8.5 | **Check-in/check-out calls:** | Our system may to configure to provide check-in/check-out calls or to provide an output when the bus reaches a user definable distance or ETA. | See response to question 8. Further discussion would be helpful to understand the full intent of this question. | Yes | All of the following data can be accepted from the on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. | The EmTrac standard report includes this information |
| 8.6 | **TSP priority level:** | We have a high priority level for EMS applications and a low priority level for TSP applications. This is defined by factory programming in the | See response to question 8. Further discussion would be helpful to understand the full intent of this question. | Yes. ACS provides presence if on time or priority request if running late. | All of the following data can be accepted from the on board computer / AVL equipment via Ethernet or serial interfaces and be transmitted to the intersections. | The vehicle equipment is configured for a specified priority level. |
vehicle equipment. It is also possible to temporarily change the priority level of a bus to high priority for applications such as emergency evacuation. This may be done via J1708 on the bus or by putting the intersection into evacuation mode via the central management software.

| 9 | What is the format of the data provided at the end of the day to be downloaded: | All data resides in the intersection equipment. The logs can be downloaded into our central management system. Reports may then be generated or logs exported in various formats such as .pdf, .xml, .csv., etc. | The proposed approach for TSP deployment is based on using on-board transit operations management and communications systems. Both the ACS OrbCAD and Continental TransitMaster systems currently support the | What is the format of the data provided at the end of the day to be downloaded: Flat File which can be uploaded into a SQL database. | Microsoft Excel-compatible CSV | Both AVL and Traffic control data is stored in an SQL or Oracle database at the central servers |
|   | Reliability of the equipment—track record from other installations: | We will be happy to provide references to other users. Also you have had our equipment installed for several years in San Francisco. | The WLAN hardware is hardened and designed for on-the-street installations, and has proven to be highly reliable where currently installed for approximately 200 intersections in the TSP approach. Both transit operations management systems offer comprehensive capabilities for capturing and downloading data. Additionally, TSP data will be captured in real time from the intersection controllers using the TSP Monitor Tool and MIST, as supported by the D4 software. | No Answer | Similar systems deployed in Chicago, Vancouver and Richmond met or exceeded the project requirements. Further information is available upon request. | Trapeze has over 20,000 vehicles installed with 99% uptime. EmTrac has never really had a failure. |
Los Angeles metropolitan area. The proposed approach for TSP deployment is based on using on-board transit operations management and communications systems. Both the ACS OrbcAD and Continental TransitMaster systems currently support the proposed TSP approach, and both systems offer impressive track records based on very high levels of hardware and software reliability.

| Security and encryption of the transmissions: | Our radios were developed in house. There is no off the shelf equivalent available. The protocol that we use is also developed in house. | The security and encryption of the transmissions depends on the radio hardware utilized and software protocols | WPA2 security is used. | Wireless - 802.11i, WPA, WPA2, WEP, TKIP, AES, FIPS 140-2 certifiable. Wired - SSL, HTTPS, SSH, SCP | Both AVL and EmTrac transmissions are encoded in a proprietary format making communications secure. |
A GPS reviver is needed for radio sync and the operation of the radio hopping is controlled by a programmed chip. Duplicating our radio would therefore be extremely difficult.

supported by the hardware. The proposed radio hardware currently supports Advanced Encryption Standard (AES-CCM), 64-bit and 128-bit WEP encryption, WPS and WPA2 WiFi Alliance certifications for WLAM security, Temporal Key Integrity Protocol (TKIP), MAC/RADIUS Server authentication, and various Extensible Authentication Protocol types including EAP-tls and EAP-passthrough.

We can monitor the door circuit via J1708 if the AVL system knows the door status. If not, the proposed TSP approach builds on using the on-board transit operations management and near side stops will cancel the request. When the door closes the request will be reinitiated.

Door contact inputs are supported. They can be monitored directly by the TSP in-

As it applies to Transit, if the vehicle has a near side stop and the vehicle detects that the door
we can sense a transition from 12 VC to ground or ground up to 12 VDC. We also have separate remote activation input which can be connected to the ignition, manual switch, or some other device.

Communication systems where the logic to initiate requests for priority will reside. Both the ACS OrbCAD and Continental TransitMaster on-bus systems currently support the proposed TSP approach. For Foothill Transit, the ACS on-bus systems interface with door open as well as with passenger stop request sensors to serve logic that cancels requests for priority at near side stops when it is known or expected that the vehicle will not be proceeding through the intersection where priority has been or will be requested.

13 Power

<p>| 13 | Power | When fully | Both the ACS shut off when not in | In addition to a low | The AVL equipment opens, the TSP request is |
| <strong>consumption—shut off when not in use? Minimum power draw?</strong> | operational the vehicle system draws about 1 amp at 12 VDC. When powered off we recommend that the unit be connected to a battery hot to keep the GPS receiver powered. When shut off, the system will draw 60 mA if set to low power mode or 100 mA if set to GPS receiver fully powered mode. If desired the unit may be wired so there is not current draw at all when shut off. | OrbCAD and Continental TransitMaster on-board systems currently support the proposed TSP approach. ACS and Continental can provide details regarding the power consumption characteristics of these systems. For the on-the-street WLAN hardware, the maximum power draw at a fully-equipped access point/network drop intersection is approximately 4.5A at 12 VDC and, for an intersection equipped as wireless client (required for about three out of every four intersections), the power consumption is | use? Minimum power draw? With a WLAN solution, the WLAN is only on when the vehicle equipment is on. The power draw is part of the normal system operations and does not vary by more than 1/2 amp whether transmitting or not. | power rating of 7W, in-vehicle equipment is powered down either immediately following ignition cut-off of vehicle, or with an optional count-down timer. has 50mA current draw when asleep. The EmTrac equipment uses 500mA to keep GPS in a ready state, although can be configured to power down completely. |</p>
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<th><strong>Ability to use existing or proposed antennas on the buses:</strong></th>
<th>0.2A at 12VDC.</th>
<th><strong>With the WLAN solution, it would use the existing WLAN antenna that is part of the on board bus solution.</strong></th>
<th><strong>For wireless communication to the intersections, Novax proposes the use of a low-profile antenna.</strong></th>
<th>Without knowing make and model it difficult to confirm. EmTrac and Trapeze prefers to replace existing antennas so that the health of the antenna starts from a known point.</th>
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<td><strong>Size of equipment:</strong></td>
<td>The antenna dimensions are listed above. The Radio/GPS unit is 8” x 4.5” x 2.7”. The vehicle control unit is 5.75” x 5.5” x 1.75”.</td>
<td>The proposed TSP system utilized the on-bus transit operations management and communications systems. Both the ACS OrbCAD and Continental TransitMaster systems currently support the proposed TSP approach. The size of the on-bus equipment is already part of the onboard AVL solution and takes no additional space.</td>
<td>PRG / PRS - 7 3/4&quot; x 5 1/6&quot; x 2 1/2&quot;, GPS - 4&quot; x 4 3/4&quot; x 1 1/4&quot;, Wireless Router - 13.2&quot; x 7.9&quot; x 5.3&quot;</td>
<td>Trapeze: IVLU - 11.4&quot; L x 8.6&quot; W x 2.5&quot; H / 3.5 lbs. MDT - 8&quot; W X 6 H X 1.5” D EmTrac: Antenna - 1.15&quot; (H) X 4.55&quot; (Diameter) VCU - 2.4&quot;(H) X 4.75&quot;(W) X 8&quot;(D)</td>
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systems equipment varies according to system requirements. No additional on-bus equipment is required for the TSP application. WLAN access point intersections are equipped with antennas and radio hardware mounted on the traffic signal pole as well as network equipment mounted on 19” by 10” panel that swings out on the rear side of the traffic controller cabinet. WLAN client intersections (typically three out of every four intersections) are equipped with a small antenna mounted on the traffic controller cabinet (or the
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<th><strong>Interference with other radio transmissions from the bus?</strong></th>
<th><strong>Our FCC part 15 radio has never received or caused interference with other radios.</strong></th>
<th><strong>None known utilizing 802.11b/g communications for vehicle-to-intersection messaging.</strong></th>
<th><strong>The vehicle antenna design will not interfere.</strong></th>
<th><strong>All equipment are fully enclosed in metal housings which keep radiation to negligible levels. In addition, with shielded cables connecting equipment, as well as careful consideration to locations of any new antennas in relation to existing ones, interference is not a concern.</strong></th>
<th><strong>Without knowing what is existing, we cannot confirm. Proper engineering can minimize any interference.</strong></th>
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<td>16</td>
<td><strong>Is your equipment used on emergency vehicles?</strong></td>
<td><strong>Yes, San Francisco Fire Department is currently using this equipment along</strong></td>
<td><strong>No.</strong></td>
<td><strong>ACS has not provided a solution for these types of vehicles, but could</strong></td>
<td><strong>Yes, our equipment has been deployed on emergency vehicles.</strong></td>
<td><strong>Trapeze – Yes EmTrac - Yes</strong></td>
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<td><strong>Will your equipment integrate with the GPS equipment that’s part of the SF Radio Project?</strong></td>
<td><strong>We would need more information about what you mean by integrate and the details of what you are looking to integrate to.</strong></td>
<td><strong>As already noted, the proposed TSP approach builds on the on-board transit operations management and communications equipment. Both the ACS OrbCAD and Continental TransitMaster on-bus systems, including the GPS equipment used for both systems, currently support the proposed TSP approach. No additional on-bus GPS or other equipment is required.</strong></td>
<td><strong>Yes</strong></td>
<td><strong>Our equipment will integrate with other vendors’ GPS equipment, provided the GPS equipment meets the accuracy requirements for TSP.</strong></td>
<td><strong>Trapeze - Trapeze would hope to be a provider EmTrac - Yes</strong></td>
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<td><strong>18</strong></td>
<td><strong>Please provide two references of agencies that use your equipment including contact information.</strong></td>
<td><strong>San Francisco FC, Cathl Hennessey.</strong></td>
<td><strong>Los Angeles County Metro – Contact: Steven Gota, (213) 922-3043 <a href="mailto:gotas@metro.net">gotas@metro.net</a>. Foothill Transit –</strong></td>
<td><strong>Foothill Transit is implementing the WLAN solution. LaShawn King Gillespie, Director of Planning at Foothill Transit, Hansel Wang Program Manager TransLink 1600 - 4720 Kingsway Burnaby, BC V5H 4N2</strong></td>
<td><strong>AVL: Minneapolis - Gary Nyburg - (612) 349-7303 - <a href="mailto:gary.nyberg@metc.state.mn.us">gary.nyberg@metc.state.mn.us</a> Long Beach - Carri Sabel - (562) 599-</strong></td>
<td></td>
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</tbody>
</table>
Contact: LaShawn Gillespie, (626) 931-7206 lgillespie@foothilltransit.org may be contacted. Her telephone number is 626-931-7206 and her e-mail address is lgillespie@foothilltransit.org.

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Novato Fire
Department Don Wehr (in charge of Emtrac) (o) 415-878-2681 (c) 415-987-4532
Coquitlam Fire Brian Olsen (Traffic Engineering) in charge of Emtrac 604-805-7247 Parson's Consultant

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| 20 | **Additional comments:** | We feel that the ease of installation, set-up and configuration of our equipment is far superior to our competition. There is no longer a need to drive a vehicle to define the preemption zones. Our zones are now easy to create on a GIS map. Any changes to parameters are done in the specific intersection. There is no need to download large databases to every vehicle when making even the smallest of changes as is the case with competitive | ACS completed this survey referring to its WLAN solution that has been developed in conjunction with Iteris. ACS is able, however, to integrate with any type of TSP solution such as Opticom, Novax, Emtrac Systems, and other solutions. | Trapeze equipment has the capability of on board annunciations, both audible and visual as well as interfaces to other systems. These system include head sign, fare collection, vehicle health monitoring. EmTrac and D4 are partnering on a project where we are using the D4 software in an EmTrac "Smart Box" as the coordinator for ETA for NEMA Machines. |
systems. We do not make use of Coax cable in our intersection equipment, eliminating possible poor connections. (The vehicle equipment antenna does use coax but they are factory termina.)