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Grade Crossing/Traffic Signal Optimization Study

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SPRINTER Rail (Phase II): Grade Crossing/Traffic Signal Optimization Study

Final Report for Task Order 6409

Prepared by:

California PATH

University of California, Berkeley

In collaboration with

North County Transit

California Department of Transportation

City of Vista

City of Escondido

City of Oceanside

City of San Marcos

San Diego County

July 2009

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16. ABSTRACT

The second phase of this project further investigates impacts to local traffic operations at intersections adjacent to signal preemption by SPRINTER commuter trains and comes up with countermeasures that not only minimize such impacts but also take into account the traffic signal coordination. An extended traffic signal optimization model has been developed to minimize overall traffic delays and the weighted width of "green band" along several coordinated traffic signals around the grade crossings. Based on the train's movement detection at grade crossings and the waiting queue estimation at the end of the preemption operation, the optimized signal timings can quickly clear the queue and still maintain coordination along the corridor of interest. This study also recommends further consideration of countermeasures involving advanced train detections.

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Executive Summary

Frequent signal preemptions and the resulting traffic and transit operational impacts significantly interrupt coordinated traffic flows. Furthermore, the safety of pedestrians and traffic vehicles at and around rail/highway grade crossings is one of the most significant traffic safety issues because most accidents at these locations cause severe injuries and often result in fatalities. Traffic congestion is already significant along the SPRINTER corridor and forecasted traffic demand indicates that dramatic increases are expected over the next 30 years. With the traffic signal preemption installed for the new SPRINTER train service, traffic congestion and safety problems will further deteriorate if traffic signal control is not optimized.

PATH, North County Transit District (NCTD), Caltrans District 11, the cities of Oceanside, Vista, San Marcos, and Escondido, and San Diego County have been working on a research project to develop methodologies to mitigate the conflict between the new SPRINTER light rail transit system and highways crossing the rail line.

Since early 2007, the research team has been working with NCTD as well as local jurisdictions to gather traffic control, traffic volume and intersection geometry data. The original optimization models have been developed and widely tested in a simulation environment.

The work documented in this report mainly represents the progress made by the research team in the following two aspects:

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- More literature review on at-grade crossings operation and technology, in particular, safety related issues, etc.
- Extension of the original traffic signal optimization model to deal with multiple traffic signals around grade crossings by taking into account traffic signal coordination.

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1. Background

Urban rail can be an effective solution to mitigate traffic congestion along major urban corridors. However, frequent preemptions at rail/highway grade crossings and the resulting delay can significantly interrupt coordinated traffic flows and threaten the safety of pedestrians and other vehicles.

1.1 Overview of the Sprinter Rail Transit

The SPRINTER Rail Transit system, which started revenue service on March 9th, 2008, is located in North San Diego County owned by the transit agency - the North San Diego County Transit District (NCTD). It extends nearly 22 miles connecting the four North County cities - Oceanside, Vista, San Marcos, and Escondido, as well as unincorporated areas of San Diego County. It serves 15 stations including a 1.7 mile loop that serves California State University San Marcos (CSUSM). The rail line parallels the heavily-congested SR 78 corridor as shown in Figure 1.

The current passenger train operates between 05:00 am and 11:00 pm and is powered by Diesel Multiple Units (DMU), either 85ft. (1 car) or 170ft. (2 cars) long, with approximately 30 minute headways and a maximum operating speed of 55mph. The train traffic control system uses traditional blocking systems and a Centralized Train Control (CTC) system. The control center is located at the maintenance facility in Escondido. The track circuits provide train presence detection for interlocking control. Near grade crossings, they also provide predicted time to arrival at the grade crossing. Figure 2

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presents an example of preemption logic which is used at one of the grade crossings along the SPRINTER rail.

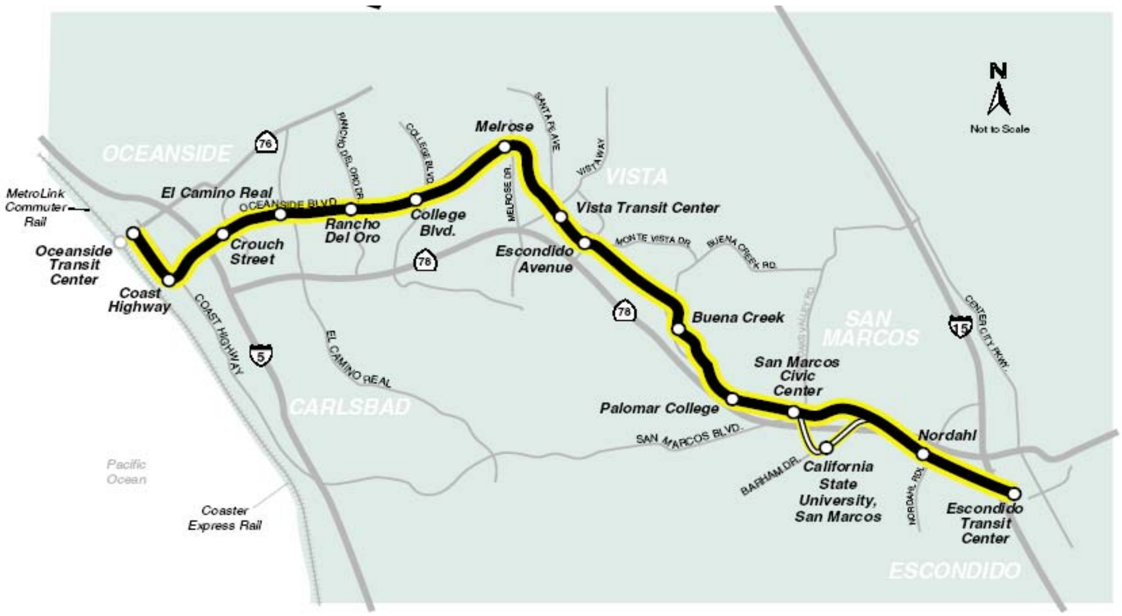

Figure 1 SPRINTER Project Site

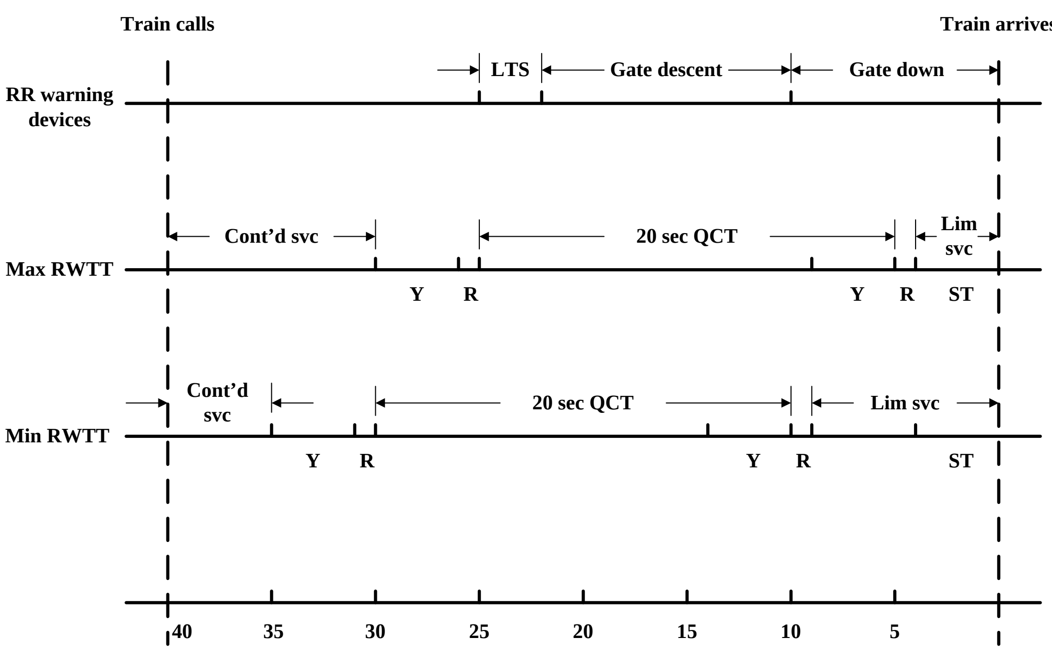

Figure 2 An Example of Preemption Logic Used in SPRINTER

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The corridor served by the SPRINTER project parallels SR78, which currently is already congested along its entire length during morning and afternoon peak periods. The project will serve large intermodal transit centers in both Oceanside and Escondido. The corridor contains a dispersed mix of commercial, industrial, and single- and multiple-family residential developments. It has also been estimated that the number of residents living in communities served by the rail line will increase by 74 percent, with employment increasing at nearly the same rate. Thus, current corridor traffic volumes are projected to increase by more than 50 percent by the year 2015, ranging from 150,000 to 200,000 vehicles per day.

In 2004, the consulting firm URS was contracted by the stakeholders along the SPRINTER line to study the possible impacts of train preemption on intersection signal operations and develop strategies to alleviate any negative impacts. However, based on our interviews with the local jurisdictions, the URS study was not performed to the satisfaction of the stakeholders.

A previous report documented by the PATH research team addressed the impacts to local traffic operations at intersections adjacent to signal preemption by SPRINTER commuter trains and proposed countermeasures that would minimize such impacts. The proposed optimization models can estimate the waiting queue at the end of the preemption operation and minimize overall traffic delays. Based on the simulation results in PARAMICS for a total of 10 intersections, the intersection delay can be reduced as much as 24 percent as a result of implementing optimal timing measures. Figure 3 shows

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the whole SPRINTER rail setup in PARAMICS. However, the optimization results are only valid for isolated intersections.

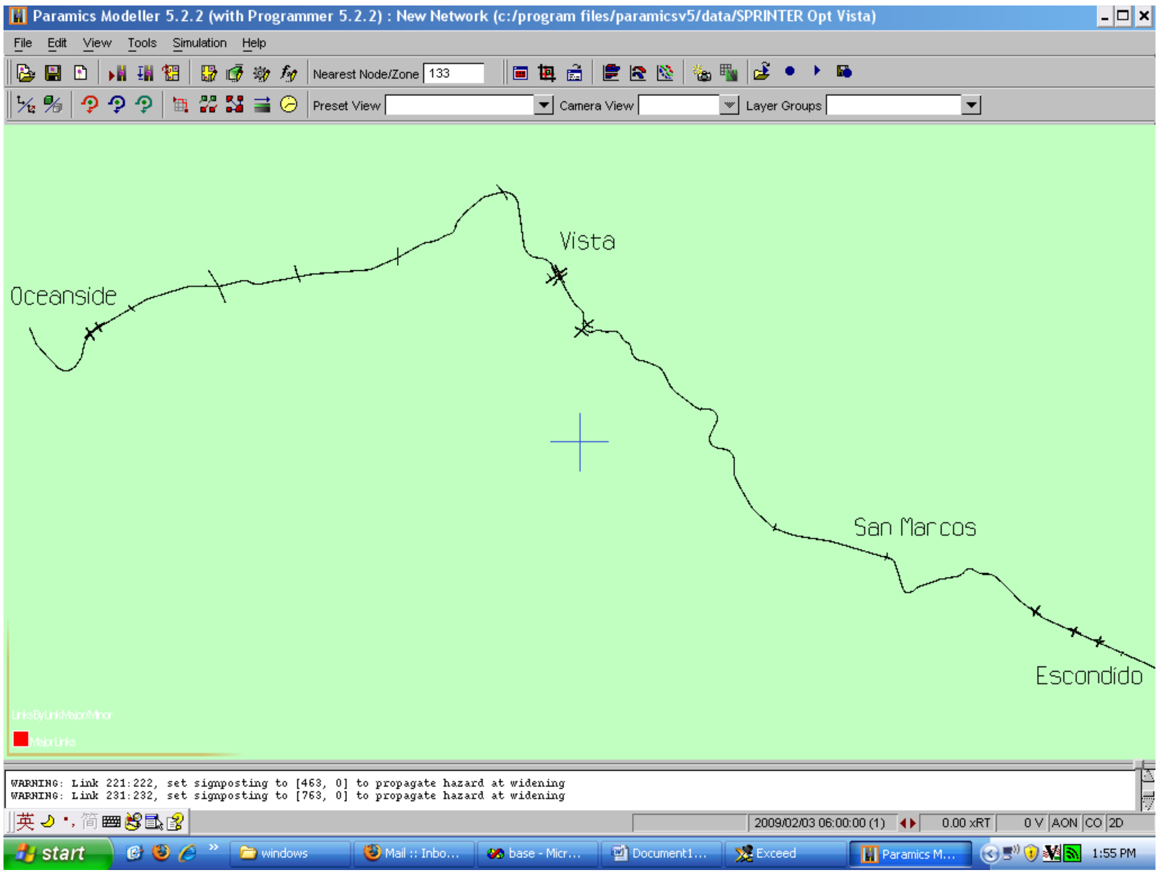

Figure 3 SPRINTER Rail Overview in PARAMICS

1.2 Safety and Efficiency Issues at Grade Crossings

The Federal Railroad Administration (FRA) has identified over 260,000 public and private grade crossings in the United States. On average, a pedestrian or a vehicle is hit by a train every two hours in the United States. Among all rail-related fatalities, 90% are connected with grade crossing and trespassing incidents. Additionally, preemption given to trains at grade crossings often generates negative impacts to the safety of pedestrians, cars and the train as well as the efficiency of other traffic.

Section 8A.01 of the Manual on Uniform Traffic Control Devices (MUTCD) defines “the transfer of normal operation of traffic signals to a special control mode” as traffic signal preemption. It is also specified in Section 8D.07 of the MUTCD: “When a highway-rail grade crossing is equipped with a flashing-light signal system and is located within 60 m (200 ft) of an intersection or mid-block location controlled by a traffic control signal, the traffic control signal should be provided with preemption in accordance with Section 4D.13.” This provision of the MUTCD is designed to ensure that the preemption sequence reaches the Track Clearance Green interval as soon as possible so that the traffic at the crossing can be cleared prior to a train’s arrival. The Track Clearance is treated with higher “relative hazard” over other control events. Consequently, the railroad preemption gives the highest ‘priority’ from the control aspect at grade crossings and interrupts any other ongoing control events, e.g. emergency vehicle preemption, pedestrian walking and clearance time, minimum and other vehicle green times. As a result, the preemptive treatment at grade crossings may result in crashes at grade crossings.

In addition to the potential hazards at grade crossings, the preemption treatment could jeopardize safety at adjacent signalized intersections. Specifically, the shortening of the pedestrian walking and clearance time can leave a pedestrian walking in the middle of a road while a conflicting track clearance movement receives green. Although not as critical as truncating pedestrian clearance time, the shortening of minimum vehicle green time may also violate drivers' expectancy and lead to unsafe driver behavior. According to a survey of operations engineers and practitioners across the United States[1], the shortening of normal pedestrian clearance and minimum vehicle green time has been ranked one of the most critical safety concerns.

Moreover, the signal control at adjacent intersections could potentially impact the safety at grade crossings. An oversaturated intersection might block traffic within the dangerous zone at a grade crossing.

Furthermore, existing preemptions at grade-crossings could seriously degrade the efficiency of traffic signal control at adjacent intersections. Preemptions often negatively impact the cross street traffic signal progression for the controlled intersections that are operating at or close to capacity. Even worse, standard traffic signal optimization[2,3] approaches do not apply, since the signal operations of these controlled intersections at grade crossings differ from those of urban signalized intersections. The sub-optimality of traffic signal timings at these intersections in the vicinity of highway-railroad grade crossings contributes to non-trivial and unnecessary waiting after a train has passed. The extra long queues might back up to upstream intersections as well. Without awareness of

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[1] Roelof J. Engelbrecht, Kevin N. Balke, Srinivasa R. Sunkari, and Steven P. Venglar; *Engineering Solutions to Improving Operations And Safety at Signalized Intersections Near Railroad Grade Crossings with Active Devices;* FHWA/TX–06/0-4265-1, September 2005

[2] A. Skabardonis, R. L.Bertini and B. R. Gallagher; *Development and Application of Control Strategies for Signalized Intersections in Coordinated Systems*; In Transportation Research Record 1634, TRB, National Research Council, Washington, D. C., 1998, pp. 110-117

[3] W-H. Lin and C-H. Wang; *An Enhanced 0-1 Mixed-Integer LP Formulation for Traffic Signal Control*; IEEE Trans. On Intelligent Transportation Systems, Vol. 5 (4), December, 2004

the preemption control, the upstream intersections might waste time on directing traffic toward a fully occupied approach. In the worst case scenario, drivers might totally block the upstream intersections for all approaches. A recent study has proposed an improved transition preemption strategy (ITPS)[4] to provide more green time to the phases that will be blocked during preemption, as compared to the normal traffic signal mode[5]. However, the optimality of overall traffic delays cannot be guaranteed. Further research on a better optimization approach is required to improve the performance of nearside intersections adjacent to at-grade crossings.

1.3 Literature Review of Grade Crossing Operation and Safety

To further improve the traffic signal operations near grade crossings, the research team continued collecting and reviewing the literature related to safety and traffic network optimization at or around grade crossings. This section summarizes the findings from the review.

1.3.1 TPS/ITPS

[4] Cho, H., and L. R. Rilett; *Improved Transitional Preemption Strategy for Traffic Signals at Intersections Near Highway-Railway Grade Crossings*; Transportation Research Board 83rd Annual Meeting, 2004

[5] Jacobson, M., Venglar, S., and J. Webb; *Advanced Intersection Controller Response to Railroad Preemption – Stage I-IV Report*; Texas Transportation Institute, Texas A&M University, College Station, Tex., May 1999-February 2000

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The Texas Transportation Institute (TTI) developed the transition preemption strategy (TPS) algorithm[6] to ensure that as the preemption was initiated by approaching trains, the signal would not change to endanger either pedestrians or drivers. In addition to a constant warning time (CWT) detector, the TPS algorithm may require an upstream detector, such as a pulse-coded track circuit, sonic detector, Doppler radar detector, AVI, or some other device, to get the constant advance preemption warning time (APWT). The time between the activation of the two detectors is the TPS operation time. However, due to the variability of the predicted arrival time, the TPS algorithm can be cut abruptly. This may result in safety problems or can apply extra green time in the track clearance phase which may give rise to excessive intersection delay. Therefore, an improved transition preemption strategy (ITPS)[7] was designed to provide more green time to the phases that will be blocked during preemption, as compared to the normal traffic signal mode and the TPS algorithm. A signalized intersection along a railway corridor in College Station, Texas was chosen as the test bed for the ITPS algorithm. A Doppler radar detector, located approximately 2.2 km (1.4 mile) upstream, can provide train speed continuously while it is in the detection area. Although no field result from the test bed was discussed in the paper, a simulation network, based on VISSIM plus vehicle actuated programming (VAP), had been set up to duplicate the test bed. Comparing standard preemption and the current TPS, the simulation results indicated that the ITPS algorithm with an APWT value of 100, 110, or 120 seconds is the more efficient operation strategy for both safety and efficiency.

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[6] Jacobson, M., Venglar, S., and J. Webb, Advanced Intersection Controller Response to Railroad Preemption – Stage I-IV Report, Texas Transportation Institute, Texas A&M University, College Station, Tex., May 1999-February 2000.
[7] Cho, H., and L. R. Rilett, Improved Transitional Preemption Strategy for Traffic Signals at Intersections Near Highway-Railway Grade Crossings, *Transportation Research Board 83rd Annual Meeting*, 2004.

1.3.2 Pseudo-real-Time Activity Detection[8]

Based on the detection input from a video camera installed in front of a locomotive, a pseudo-real-time ego-motion (camera-motion) estimation method with a robust optimization algorithm was developed to automatically extract possible near-accident scenes by detecting vehicle activity crossing in front of the train after signals begin. A preliminary experimental test on a small volume of video data showed that approximately 50 – 150 ms was required for the corner detection and matching, and 20 – 500 ms (mostly less than 150 ms) was spent for the optimization, respectively.

1.3.3 SOURCAO[9]

SOURCAO (Signal Optimization Under Rail Crossing sAfety cOnstraints) was developed with respect to two target objectives. One is for highway-rail grade crossing safety improvement, while the other is for highway traffic delay reduction. On the one hand, highway-rail grade crossing safety was promoted by intelligently choosing a proper preemption phase sequence resulting from the output of SOURCAO. On the other hand, optimal phase length was also available by minimizing the network traffic delay at the intersections within the highway-rail grade crossing safety vicinity. Due to the complexity of the delay function, a multilayer perceptron neural network approach was proposed as an offline approximation and Successive Quadratic Programming (SQP)

[8] Kim, Z. and T. E. Cohn, Pseudoreal-Time Activity Detection for Railroad Grade-Crossing Safety, IEEE ITS. Vol. 5. No. 4, 2004. pp. 319 - 324

[9] Zhang, L. Optimizing Traffic Network Signals around Railroad Crossings. Ph. D. Thesis, Virginia Polytechnic Institute, 2001.

was used to search the length of phases (online) after the model was trained. Statistical tests on the data from independent simulation evaluation wereconducted and demonstrated the validity and efficiency of SOURCAO. However, it is difficult to implement SOURCAO in the field because the model assumptions are too strong and the required information is too much.

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2. Problem Identification

With the train preemption interrupting regular traffic operations, the coordination may be imperfect along the signalized intersections adjacent to the grade crossings. The research team verified this potential problem mainly through the input from local jurisdictions, e.g. City of Vista.

2.1 Concerned Sites

Based on meetings atNCTD and correspondence with the traffic engineers from the City of Vista, there are a lot of concerns regarding traffic signal coordination after preemption at the following sites in the City of Vista: Olive @ Vista Village Dr, Santa Fe Ave @ Vista Village Dr. and Santa Fe Ave @ Main. Figure 4 shows these three intersections in displayed PARAMICS. In addition, these three signalized intersections are very close to one another and the distance between two grade crossings is only 90 meters. If the traffic signals are not coordinated, long queues and inefficiency of the traffic network around these sites may be expected.

2.2 Inputs from City of Vista

In the last meeting on Feb 4th, 2009, the traffic engineers from City of Vista expressed their concerns regarding the impact of preemption operations on the current coordinated corridor. Since the sites chosen by City of Vista are very close to one another, it is more

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desirable to minimize the impacts on the coordination at Olive @ Vista Village Dr, Santa Fe Ave @ Vista Village Dr. and Santa Fe Ave @ Main., compared with the other study sites along the SPRINTER rail corridor. In the correspondence with those traffic engineers from City of Vista in March and April, they provided more information related to coordination, which will be used as the input of our extended optimization model (please refer to Chapter 3 for more details).

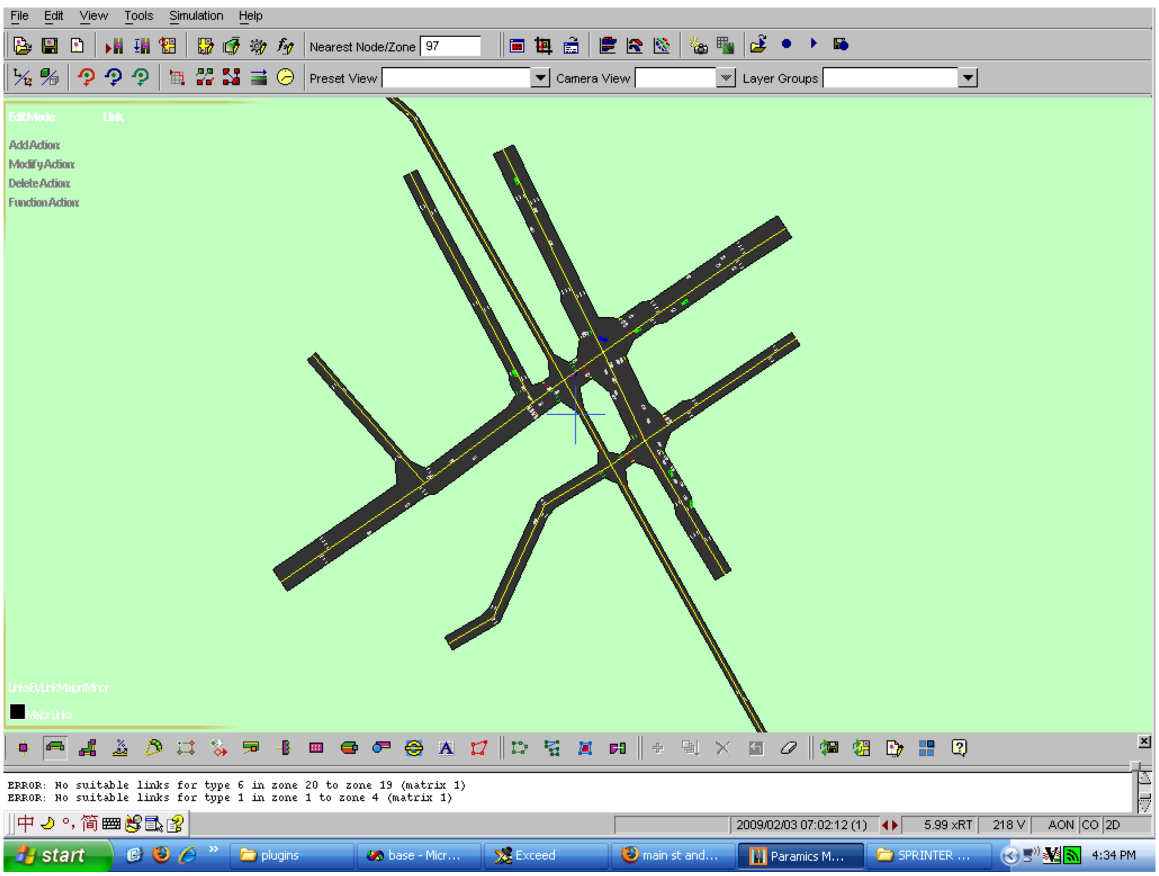

Figure 4. Concerned Sites in City of Vista coded in PARAMICS

2.3 Other Concerns

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Based on the meetings and correspondence with local jurisdictions, other concerns related to the SPRINTER preemption operation may include but are not limited to:

- Pre-signal (Escondido)
- Pedestrian safety

Pre-signals (required by the California Public Utilities Commission) are typically used when, due to horizontal or vertical alignment of the roadway, the signals at the intersection adjacent to a railroad crossing could not be viewed clearly from a distance. Under this situation, a pre-signal is installed ahead of the regular signal to inform and control traffic flowing toward the regular signal. The signal head display on the pre-signal is usually exactly the same as that shown on the related regular signal. The concern with the use of the pre-signal is for the time lost in each cycle, both at the beginning and the end of the phase serving the track crossing approach, since the vehicles will need a few seconds to travel the distance between the pre-signal and the regular signal. Figure 5 shows a pre-signal example near the AutoPark Way and Nordahl Road intersection in the City of Escondido. As shown in Figure 5a, for northbound vehicles traveling toward the railroad track, the horizontal curve prevents them from having a clear view of the signals at the railroad crossing, thus, a pre-signal is now installed at the location that was previously marked with a railroad crossing sign (Figure 5b).

Pedestrian safety, especially when the public is still unfamiliar with railroad crossing operations, was a concern expressed by both cities. Public education should be emphasized as well as pedestrian protection that’s built into the traffic signal operations during the preemption period.

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(a) (b)

Figure 5 Pre-signal location at Auto Park Way and Nordahl Road in the City of Escondido

This report mainly focuses on minimizing the preemption operation impacts on the coordination of traffic signals around grade crossings.

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3. Extension of Signal Timing Optimization Model

3.1 Model Assumptions

As has been identified in the previous report, the signal timing optimization model developed is only for an isolated intersection, although the optimization period can be longer than one cycle. To take into account the coordination of several signalized intersections around grade crossings and simplify the problem statement, we may need to make the following assumptions:

- The area of interest consists of three traffic signals and these signals are coordinated under normal operation.
- Only the intermediate signal will be interrupted by train preemption.
- We will not adjust timings for the other two signals except the intermediate one.
- Movement 2 and movement 6 of the intermediate intersection are coordinated, where movement 2 represents bound 1, and movement 6 represents bound 2 in the following problem formulation
- The studied intersection is running fixed timings;
- The arrival rate, a_i for each phase is uniform and constant;
- The dissipation rate, d_i, is constant and relates to the road characteristics;
- In most cases, the controlled time-span is one cycle after the train clears the grade-crossing, but the model can also be extended to the controlled time-span of multiple cycles.
- The traffic condition is under-saturated.

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- Vehicles accelerate and decelerate instantaneously, which implies that all drivers behave identically, i.e. they follow average driving patterns.
- In timing optimization, the sequence of phases (lead/lag relationship) remains untapped during the controlled time-span.
- The dual-ring signal controller is used for traffic control at the intersection.

3.2 Objective Function

Our goal is to design green splits for different phases after the preemption, such that the total intersection delay can be minimized over the controlled time period. In addition, the coordination should not be bungled by the SPRINTER preemption. Therefore, the objective function is two-fold: one is the overall traffic delay at the signalized intersection of interest, and the other is the "green band" width of the coordinated corridor.

3.2.1 Delay Quantification

The delay term in the extended traffic signal optimization is the same as that documented in the previous report, i.e.

$$\sum_{j=1,2}\sum_{i\in D_j}\Big\{n_i(TTA,PD)\cdot C+\frac{1}{2}\cdot a_i\cdot C^2-\frac{1}{2}\cdot d_i\cdot\left(g_{i,2}-g_{i,1}\right)^2-\frac{1}{2}\cdot\left[2\cdot d_i\cdot\left(g_{i,2}-g_{i,1}\right)+a_i\cdot\left(g_{i,3}-g_{i,2}\right)\right]\cdot\left(g_{i,3}-g_{i,2}\right)-\left[d_i\cdot\left(g_{i,2}-g_{i,1}\right)+a_i\cdot\left(g_{i,3}-g_{i,2}\right)\right]\cdot\left(C-g_{i,3}\right)\Big\}$$

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3.2.2 Width of Green Band

The width of green band is directly related to the green splits of successive signalized intersections and the average travel time of normal traffic flow. If we choose the start point, $GB_{i,j}^{S}$ and end point, $GB_{i,j}^{E}$ of the green band along the *j*-th bound at intersection *i* as the decision variables, then we will have the second term of the objective function (according to our assumptions above, *i* =2 and *j* = 1 or 2)

$$[(GB_{2,1}^{E} - GB_{2,1}^{S}) + (GB_{2,2}^{E} - GB_{2,2}^{S})]$$

Since the problem is a multi-objective program (MOP), it is desirable to add different weighting factors for different terms of the objective function, or,

$$\omega_1 \cdot (GB_{2,1}^{E} - GB_{2,1}^{S}) + \omega_2 \cdot (GB_{2,2}^{E} - GB_{2,2}^{S})$$

3.3 Constraints

Compared with the original traffic signal timing optimization model, the constraints of the extended model can be mainly divided into two portions: one portion of the constraints still come from the mechanism of the dual-ring signal controller, such as the sequence of phases, the barrier constraint and the bound on adjustable parameters. The sequence of phases is dependent on the specific site. For example, in the model shown below, there are eight phases and the lag phases are 2, 4, 6, and 8. Modifications on constraints can be easily made for other phase sequences. For the safety issue, the designed length of each green phase should not exceed the maximum green, but must be

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longer than the minimum green requirement. The other portion of the constraints is related to the geometry of the green band, which is not considered in the original model.

3.4 Summary

3.4.1 Mixed Integer Quadratic Programming (MIQP) Model

Combining the objective function as well as the constraints, we also formulate our problem into a mixed integer quadratic programming (MIQP) model. Our goal is to minimize the overall traffic delay at the intersection near the grade crossing after the preemption, and at the same time minimize the impacts on the coordination.

$$\min \sum_{j=1,2} \sum_{i \in D_j} \Big\{ n_i(TTA, PD) \cdot C + \frac{1}{2} \cdot a_i \cdot C^2 - \frac{1}{2} \cdot d_i \cdot \left(g_{i,2} - g_{i,1}\right)^2 - \frac{1}{2} \cdot \left[2 \cdot d_i \cdot \left(g_{i,2} - g_{i,1}\right) + a_i \cdot \left(g_{i,3} - g_{i,2}\right)\right] \cdot \left(g_{i,3} - g_{i,2}\right) - \left[d_i \cdot \left(g_{i,2} - g_{i,1}\right) + a_i \cdot \left(g_{i,3} - g_{i,2}\right)\right] \cdot \left(C - g_{i,3}\right) \Big\} + \omega_1 \cdot \left(GB_{2,1}^{E} - GB_{2,1}^{S}\right) + \omega_2 \cdot \left(GB_{2,2}^{E} - GB_{2,2}^{S}\right)$$

s.t.

$$n_i(TTA, PD) - d_i \cdot \left(g_{i,2} - g_{i,1}\right) \le 0 \qquad i \in D_j \text{ and } j = 1,2 \qquad (1)$$

$$d_i \cdot \left(g_{i,2} - g_{i,1}\right) - \left[n_i(TTA, PD) + a_i \cdot g_{i,2}\right] \le 0 \qquad i \in D_j \text{ and } j = 1,2 \qquad (2)$$

$$g_{i,3} - g_{i,1} - G_i^{max} \le 0 \qquad i \in D_j \text{ and } j = 1,2 \qquad (3)$$

$$g_{i,1} - g_{i,3} + G_i^{min} \le 0 \qquad i \in D_j \text{ and } j = 1,2 \qquad (4)$$

$$g_{p_j^{k+1},1} - g_{p_j^k,3} - y_{p_j^k} - r_{p_j^k} = 0 \qquad j = 1,2, \text{and } k = 1,2,3 \qquad (5)$$

$$g_{p_j^1,1} - y_{p_j^4} - r_{p_j^4} = 0 \qquad j = 1,2 \qquad (6)$$

$$g_{p_1^1,1} - g_{p_2^1,1} = 0 \qquad \text{and} \qquad g_{p_1^3,1} - g_{p_2^3,1} = 0 \qquad (7)$$

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$$GB^S_{k+1,1} - GB^S_{k,1} = Tr_{k,k+1} \text{ and } GB^E_{k+1,1} - GB^E_{k,1} = Tr_{k,k+1} \qquad k = 1,2 \quad (8)$$

$$GB^S_{k,2} - GB^S_{k+1,2} = Tr_{k+1,k} \text{ and } GB^E_{k,2} - GB^E_{k+1,2} = Tr_{k+1,k} \qquad k = 1,2 \quad (9)$$

$$g_{k,2,1} + O_k + C \cdot n_{k,1} \leq GB^S_{k,1}, GB^E_{k,1} \leq g_{k,2,3} + O_k + C \cdot n_{k,1} \qquad k = 1,2,3 \quad (10)$$

$$g_{k,6,1} + O_k + C \cdot n_{k,2} \leq GB^S_{k,2}, GB^E_{k,2} \leq g_{k,6,3} + O_k + C \cdot n_{k,2} \qquad k = 1,2,3 \quad (11)$$

$$GB^E_{k,l} - GB^S_{k,l} \geq GB^{min}_l \qquad k = 1,2,3 \text{ and } l = 1,2 \quad (12)$$

$$g_{p_j^4,3} - C = 0 \qquad j = 1,2 \quad (13)$$

$$0 \leq g_{i,1} \leq g_{i,2} \leq g_{i,3} \leq C \qquad i \in D_j \text{ and } j = 1,2 \quad (14)$$

Constraint (1) guarantees that vehicles will not wait for over one cycle, and constraint (2) represents the restriction on the value that $g_{i,2}$ can take. Constraints (3) and (4) relate the safety concerns on minimum and maximum green for each phase. Constraints (5) – (6) are the connectivity (sequence) condition for phases in each ring, where p_j^k means the k-th phase in the j-th ring. Constraint (7) represents the barrier condition for the dual ring signal controller, which means that phase(s) must terminate their timing and cross the "barrier" together. Constraints (8) – (11) are feasibility conditions for the green bands of both bounds along the area of interest. Users can define the minimum width of green band of each bound by changing the RHS of constraint (12). Constraint (13) ensures the cycle length will not change. The last constraint shows the upper bound and lower bound for each decision variable, where $g_{i,1}$'s and $g_{i,3}$'s must be integers.

3.4.2 Multiple-Cycle Version

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Similar to the original optimization model, if the traffic volume along the coordinated phases increase and/or the preemption duration is too long, we might not obtain a feasible solution if we apply the optimization model mentioned in previous sections. This infeasibility is due to the ambition to clear the queue that is backed up during preemption within a single cycle. By modification, we can obtain a more generalized MIQP model, i.e. a multi-cycle version of the traffic signal optimization model. The queue does not necessarily have to be cleared up within one cycle, but within $m(\geq 1)$ cycles, where m is a user-defined value. In addition, it is evident that the optimization model presented above is a special case of this multi-cycle optimization model when $m = 1$.

$$\min \sum_{j=1,2} \sum_{k \in D_j} \Big\{ n_k(TTA, PD) \cdot m \cdot C + \frac{1}{2} \cdot a_k \cdot (m \cdot C)^2 - \Big\{ \sum_{i \in M} \frac{1}{2} \cdot d_k \cdot \left(g_{i,k,2} - g_{i,k,1}\right)^2 + \frac{1}{2} \cdot \left[2 \cdot d_k \cdot \left(g_{i,k,2} - g_{i,k,1}\right) + a_k \cdot \left(g_{i,k,3} - g_{i,k,2}\right)\right] \cdot \left(g_{i,k,3} - g_{i,k,2}\right) + \left[d_k \cdot \left(g_{i,k,2} - g_{i,k,1}\right) + a_k \cdot \left(g_{i,k,3} - g_{i,k,2}\right)\right] \cdot \left(m \cdot C - g_{i,k,3}\right) \Big\} \Big\} + \omega_1 \cdot \left(GB_{2,1}^{E} - GB_{2,1}^{S}\right) + \omega_2 \cdot \left(GB_{2,2}^{E} - GB_{2,2}^{S}\right)$$

subject to

$$n_k(TTA, PD) + a_k \cdot (i-1) \cdot C - d_k \cdot \sum_{l=1}^{i} \left(g_{l,k,2} - g_{l,k,1}\right) \leq 0 \qquad \forall i \in M, j = 1, 2, and\ k \in D_j \qquad (1)$$

$$d_k \cdot \sum_{l=1}^{i} \left(g_{l,k,2} - g_{l,k,1}\right) - \left[n_k(TTA, PD) + a_k \cdot g_{i,k,2}\right] \leq 0 \qquad \forall i \in M, j = 1, 2, and\ k \in D_j \qquad (2)$$

$$g_{i,k,3} - g_{i,k,1} - G_k^{max} \leq 0 \qquad \forall i \in M, j = 1, 2, and\ k \in D_j \qquad (3)$$

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$$g_{i,k,1} - g_{i,k,3} + G_k^{min} \le 0 \qquad \forall i \in M, j = 1, 2, and\ k \in D_j \qquad (4)$$

$$g_{i,p_j^{k+1},1} - g_{i,p_j^k,3} - y_{p_j^k} - r_{p_j^k} = 0$$

$$\forall i \in M, j = 1, 2, and\ k = 1,2,3 \qquad (5)$$

$$g_{i,p_j^1,1} - g_{i-1,p_j^4,3} - y_{p_j^4} - r_{p_j^4} = 0$$

$$\forall i \in M, and\ j = 1, 2 \qquad (6)$$

$$g_{0,p_j^4,3} = 0 \qquad \forall j = 1, 2 \qquad (7)$$

$$g_{i,p_1^1,1} - g_{i,p_2^1,1} = 0 \quad \text{and} \quad g_{i,p_1^3,1} - g_{i,p_2^3,1} = 0 \qquad \forall i \in M \qquad (8)$$

$$GB_{l+1,1}^S - GB_{l,1}^S = Tr_{l,l+1} \text{ and } GB_{l+1,1}^E - GB_{l,1}^E = Tr_{l,l+1} \qquad l = 1, 2 \ (9)$$

$$GB_{l,2}^S - GB_{l+1,2}^S = Tr_{l+1,l} \text{ and } GB_{l,2}^E - GB_{l+1,2}^E = Tr_{l+1,l} \qquad l = 1, 2 \ (10)$$

$$g_{l,2,1} + O_l + C \cdot n_{l,1} \le GB_{l,1}^S, GB_{l,1}^E \le g_{l,2,3} + O_l + C \cdot n_{l,1} \quad l = 1, 2, 3 \ (11)$$

$$g_{l,6,1} + O_l + C \cdot n_{l,2} \le GB_{l,2}^S, GB_{l,2}^E \le g_{l,6,3} + O_l + C \cdot n_{l,2} \quad l = 1, 2, 3 \ (12)$$

$$GB_{l,q}^E - GB_{l,q}^S \ge GB_l^{min} \qquad l = 1, 2, 3 \text{ and } q = 1, 2 \ (13)$$

$$g_{i,p_j^4,3} - i \cdot C = 0 \qquad \forall i \in M, and\ j = 1, 2 \qquad (14)$$

$$(i-1) \cdot C \le g_{i,k,1} \le g_{i,k,2} \le g_{i,k,3} \le i \cdot C$$

$$\forall i \in M, j = 1, 2, and\ k \in D_j \qquad (15)$$

It is noted that the descriptions of all constraints are similar to those in section 3.4.1.

3.5 Discussion

- Although we setup the above model based on a three-signal arterial, it is not involved to the extent of other types of signalized corridors.

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- By adjusting two weighting factors in the objective function, we can balance the performance of the whole traffic network along both coordinated approach(es) and the cross-street.
- One major flaw of this model is the assumption of a uniform arrival pattern. Under the coordination, motor vehicles should approach the intersection in platoon instead of randomly. Thus, biases will be expected in queue length estimation and delay quantification.

The following symbols are used in this chapter

M = The cycle index set, i.e. $M = \{1, 2, \dots, m\}$.

D_1 = The phase set of the first ring in the dual ring signal controller in our case study, $D_1 = \{3, 4, 1, 2\}$.

D_2 = The phase set of the first ring in the dual ring signal controller in our case study, $D_2 = \{7, 8, 5, 6\}$.

C = The cycle length (sec).

TTA = The time of the local clock when the train triggers the preemption, or the preemption initiation time (sec).

PD = Preemption duration (sec).

$n_i(\cdot,\cdot)$ = The number of waiting vehicles along the ith phase after the preemption, it is a function of TTA and PD (veh).

a_i = The arrival rate of traffic along the i-th phase (veh/sec).

d_i = The departure rate of traffic along the i-th phase (veh/sec).

$g_{i,1}$ = The green start along the i-th phase on the local clock (sec).

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$g_{i,2}$ = The green clear point along the i-th movement on the local clock (sec). If the queue is cleared, then $g_{i,2} = [n_i(TTA, PD) + d_i \cdot g_{i,2}]/(d_i - a_i)$, else, $g_{i,2} = g_{i,3}$.

$g_{i,3}$ = The green end along the i-th phase on the local clock (sec).

$g_{i,j,1}$ = The green start along the j-th phase on the local clock in the i-th cycle after the preemption (sec).

$g_{i,j,2}$ = The green clear point along the j-th phase on the local clock in the i-th cycle after the preemption (sec).

$g_{i,j,3}$ = The green end along the j-th phase on the local clock in the i-th cycle after the preemption (sec).

G_i^{max} = The maximum green along the i-th phase on the local clock (sec).

G_i^{min} = The minimum green along the i-th phase on the local clock (sec).

y_i = The yellow duration along the i-th phase on the local clock (sec).

r_i = The red clearance along the i-th phase on the local clock (sec).

p_j^k = The k-th phase in the j-th ring.

$GB_{i,j}^S$ = The start point of the green band along j-th bound at the i-th intersection

$GB_{i,j}^E$ = The end point of the green band along j-th bound at the i-th intersection

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4. Conclusion and Future Steps

The SPRINTER Rail Transit Project is located in northern San Diego County. The rail line parallels the heavily-congested SR 78 corridor and is currently used in temporal and special separation by both freight and passenger transportation. It extends nearly 22 miles and connects the four North County cities - Oceanside, Vista, San Marcos, and Escondido, and unincorporated areas of San Diego County. The SPRINTER line started revenue service in March 2008.

In the project area, traffic congestion is already prevalent and traffic demand is increasing dramatically. With the traffic signal preemption provided to the new train service, the traffic congestion problem will further deteriorate if traffic signal control is not optimized. Furthermore, due to the traffic signal coordination at some study sites, e.g. Olive @ Vista Village Dr, Santa Fe Ave @ Vista Village Dr. and Santa Fe Ave @ Main. in City of Vista, such interruption by the SPRINTER preemption operation may get even worse.

The research team worked closely with NCTD as well as the local jurisdictions to gather traffic control, traffic volume, and intersection-focused geometric information. The research team has extended the original model to better address the above issue. The extended optimization model not only minimizes overall traffic delay at an intersection after the train preemption operation ends but also minimizes the weighted green band width such that the coordination can be guaranteed to some extent.

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However, one major flaw of the extended model is that the arrival flow rate is assumed to be uniform due to the lack of further information on traffic flows. Yet, such an assumption does not hold for coordinated corridors in general. With further information available, the model can be refined to overcome the above shortcoming.

The proposed extended traffic signal optimization model needs to be coded and solved by state-of-the-art optimization software, such as CPLEX, LINDO, etc. Further verification can be performed by simulation evaluation models (PARAMICS, VISSIM, etc.). If possible, the extended optimization model should be calibrated using more updated and reliable information (for instance, traffic volume data), so that the optimized signal timing plans are more reliable and ready for field testing.