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Control strategies of traffic signal timing transition for emergency vehicle preemption

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ABSTRACT

Emergency vehicle (EV) operation saves lives and reduces property damage. This paper reports two new control strategies for EV signal pre-emption (EVSP) that reduce the response time and minimize the impact of EV operation on general traffic. A real-time control strategy is developed that enables signal transitioning from normal operation to EVSP (transition 1) so that the approaching EV can cross the intersection safely at its operating speed and also the impact of the EVSP on general traffic is decreased. The green time that is not required for the EV is dynamically allotted to the traffic on the cross road by taking into account the prevailing traffic condition at the intersection and the state of signal indication. The second control strategy, implemented by an optimal control algorithm, is used for the signal transitioning from the EVSP back to normal operation (transition 2). A two-phase algorithm, consisting of a relaxation method and a stepwise search strategy, is adopted to overcome the difficulty in solving the optimal control model, which results from the interrelationship between successive signal sequences. Software was developed in the MATLAB environment for simulations of the EVSP process under different signal timing transitioning control strategies. Results indicate that the real-time control and the optimal control strategies and their associated methods perform better than the commonly used existing approaches. It is also demonstrated that the two control strategies are applicable to different traffic conditions up to and slightly over-saturated level, and can be used to deal with a single EVSP occurrence as well as multiple EVSP occurrences.

1. Introduction

During emergency operation, it is a challenge to ensure safe passage of an emergency vehicle (EV) or multiple EVs and at the same time to maintain safe and smooth traffic flow in the road network. Generally, from almost daily small incidents to major disasters, police, fire fighters and ambulances are required to reach the emergency scene for initial lifesaving and scene stabilization. Frequently, existing congested traffic conditions make it difficult for EVs to arrive at the scene in a quick and safe manner. On the other hand, it is not uncommon that EV operations cause congestion and sometimes become involved in incidents and accidents (US DOT, 2002; TRB, 2002).

From the perspective of traffic control, EV operations require attention at the network level as well as at the intersection level. The task at the network level is to determine the quickest route from the origin of an EV to its destination, so that the EV can reach the scene at the earliest possible time along the selected route. The requirement at the intersection level is to ensure that the EV can pass in a quick and safe manner.

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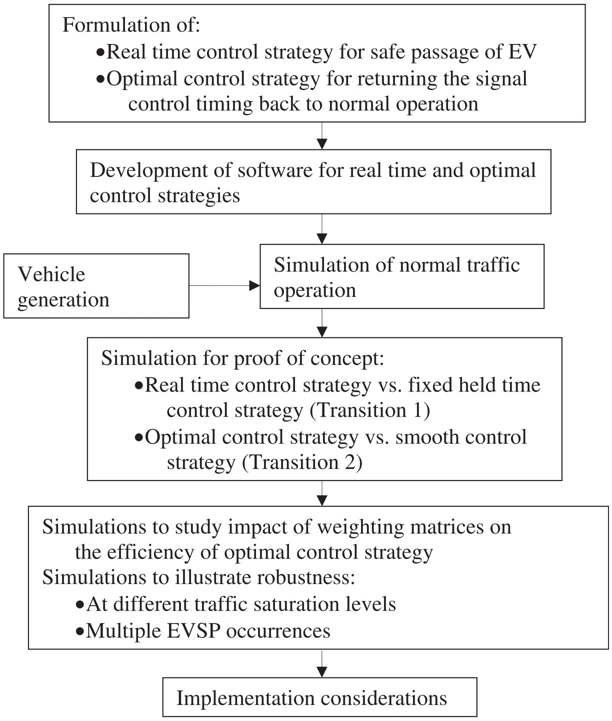

Fig. 1. Research framework.

Considering the importance of EV operations in saving lives and reducing property damage, preferential treatment is given to ensure the success of EV operations. One of the preferential treatments is emergency vehicle signal preemption (EVSP) at the signalized intersection (FHWA, 2006a; Deeter et al., 2001). When an EV approaches a signalized intersection, it requests preferential signal indication for crossing the intersection. Once the EVSP system receives the request, it interrupts normal signal operation and offers green indication. After the EV has passed through the intersection, the EVSP system gets the signal control back to normal operation. Because the pre-emption causes disruption of normal signal operation, especially in a coordinated signal system, effective strategies are needed to control the transition of traffic signals in a safe mode and reduce the impact on general traffic to a minimal possible level.

It is possible to find a way to let an EV clear each intersection at its operating speed, and at the same time to keep the disruption on general traffic at an acceptable level. The task at the network level in most situations will be to select the quickest route between the origin of the EV and its destination. In the case of road segments and intersections, which are of interest in this study, detailed methods supported by advanced technology are required. This paper reports research that focuses on the traffic signal control at isolated as well as coordinated intersections. The research framework shown as Fig. 1 consists of methodological steps of formulating control strategies, development of software for analyzing these in a simulation test bed, obtaining proof of concept, and conducting robustness tests.

The whole process of EVSP is divided into two periods, called transitions. Transition 1 is from the instant an EV is detected at an approach to an intersection to the moment the EV just passes through the intersection. Transition 2 is from the time the EV crosses the intersection to the moment when traffic signal control returns to normal operation. The objectives of research reported here were to (1) formulate a real-time signal control strategy to ensure the safe clearance of the EV at the intersection without stopping or reducing operating speed, and to decrease the impact on general traffic to a minimal extent, (2) develop an optimal control model for signal timing to minimize traffic queues at the intersection during a shortest possible period of recovery time after the EV clears the intersection, and (3) develop software for simulating traffic during EV operations and verification of the efficiency of proposed signal control strategies.

2. The EVSP system

2.1. Advanced technology component

The concept of EVSP is not new since it was first suggested in 1929 (FHWA, 2006a). However, due to the availability of Intelligent Transportation System (ITS) technologies, the problem of EVSP can now be dealt with on a real-time basis. There already exist several commercial systems that allow EVs to request and receive green indications. Leading examples of traffic signal preemption system include OPTICOM system from 3M Corporation Inc. (Nelson, 2003), STROBECOM system from Tomar Electronics Inc. (2005), and MIRT system from Platinum One Net Inc. (2005).

A typical EVSP system consists of (1) a signal emitter, which is mounted on the EV, (2) EV sensors (detectors), which are installed along the road and on/near traffic signals, (3) a traffic signal controller, and (4) traffic signal indicators. When an EV is en route to an emergency, its emitter sends signals for preemption. As sensors receive the signal that an EV is approaching and is within their operational range, a control mechanism stored in the traffic signal controller is activated, and signal indicators are instructed to interrupt normal operation and provide green indication to the EV until it crosses the intersection.

It is useful to briefly describe technologies used for EV detection. The pavement invasive technologies include inductive loops, compact wireless sensors/detectors, magnetometers, and magnet-based technologies. The non-pavement invasive detectors include microwave radar, active and passive infrared based equipment, ultrasonic and acoustic detectors and video image processing (Bachelder and Foster, 2004; FHWA, 2006b). Global Positioning Systems (GPS)-based EVSP systems (Thompson and Nicholls, 1997; FHWA, 2006a) are also used to obtain the position, speed, and heading of EVs, and the information is used to provide a green wave for EVs en route to emergencies.

For EV detection in the vicinity of an intersection, more advanced and recent systems use the combination of two phase/differential GPS and digital short range communication (DSRC) technologies (Industry Canada, US DOT, 2011). In the existing practice of EV detection and arrival time prediction supported by advance technology (e.g. GPS and short range radio-based system), selectable distance/time-points are established by traffic operations personnel by taking into account on-street congestion.

As a part of emerging "connected vehicles" technology, the DSRC is being tested for emergency vehicle signal priority (among numerous applications for public safety and traffic management). In association with existing technology such as GPS and on-board equipment, vehicles are able to broadcast their location message at 5.9 GHz. This technology enables all equipped vehicles to share data with other vehicles and infrastructure-based units such as speed and location. The on-board technology is used to sense the presence of other nearby vehicles and infer traffic flow states (Barry, 2011).

Although a variety of EV detection systems have been developed as noted above, the control mechanism, which alters the traffic signal timing plans in a safe and efficient manner, is not well researched. In this paper, it is assumed that all ITS technologies required for EV operations are in place and communication among individual devices is assured. Therefore, only control strategies of signal timing and corresponding methods for their implementation that were developed in this research are described.

2.2. Control strategies

In many older EVSP systems, a green wave is provided along fixed EV corridors, usually fire routes, by pushing a button in the fire station (or by remote request from the emergency service control centre). The fire route stays in effect for a specified period of time or until the switch is turned off (FHWA, 1996). More modern EVSP systems are implemented through real-time control strategies. Special detectors receive coded signals from the EV or EV and infrastructure-based system or GPS plus DSRC system, and then the EVSP system preempts regular signal phasing to allow a green indication in the direction needed by the approaching EV (FHWA, 1996, 2006a; Industry Canada, 2007).

A number of "selected vehicle" priority systems are in operation in North America and Europe which can accommodate transit priority as well as EV priority requirements in the their high level design architecture. These systems use common vehicle detection technology. In some systems, emergency vehicle priority is an adaptation of a public transport priority scheme, but the emergency vehicle receives a higher level of priority. A literature review on "selected vehicle" priority systems that have been implemented can be found in Fox et al. (1998).

In many traffic signal control systems, simplifying assumptions are made that the EVSP can be regarded to be similar to transit priority and the control strategy is the same for both EV and transit, except that the EV has a relatively higher level of priority (Fox et al., 1998; Nelson and Bullock, 2000). Another simplification made in the design of older EVSP systems is the adoption of a pre-timed control strategy, and current traffic condition is not taken into consideration for changing traffic signal indications.

A variety of adaptive traffic control systems have become available (Janos and Furth, 2002; Urbanik et al., 2003). Also, research and development efforts have been reported to include the transit priority as well as EV priority features in these software for the purpose of developing a single, integrated traffic control system (Collura et al., 2006). As a note of caution, it has been pointed out in the literature that the algorithm for transit priority cannot be used for EVSP without necessary modifications. This was in response to attempts that have been made to use transit priority software for EVSP as well and by doing so the difference in nature of transit and emergency vehicle operations was not taken into account.

Transit priority and the EVSP are in fact different processes (ITS America, 2002). Transit priority accommodation is often conditional upon satisfaction of pre-defined conditions (e.g., absence of a pedestrian phase) and on the other hand emergency vehicle preemption is usually conditional on the absence or (completion) of the pedestrian phase. Therefore, developers of advanced traffic controllers should be aware of the differences between transit priority and EV priority algorithms while planning their co-existence within the software (Collura et al., 2006).

While much research has focused on the impact of transit priority (Rakha and Zhang, 2004; Daniel et al., 2004; Dion et al., 2004; Baker et al., 2004), the impact of EV preemption has not been well studied. Specifically, few research results are available on the control mechanism of signal timing transition that is necessary for EV accommodation (i.e., from normal operation to EVSP and back to normal operation).

When an EV approaches an intersection, it requests signal preemption. For the commonly used fixed held time control strategy, after the EVSP system receives the request, it interrupts normal operation and provides a specified period of green time for the EV route. If such a green time is not long enough to clear the EV, another period of green time will be provided. This process will continue until the EV crosses the intersection.

After the EV has crossed the intersection, the signal control needs to be brought back to normal operation in a safe and expedient manner. The commonly used transition algorithms for this recovery period include (Nelson and Bullock, 2000):

(1) *Smooth transitioning*. The local cycle length is adjusted by adding or subtracting time up to a certain maximum amount per cycle. The implementation consideration is the quickest recovery back to the coordination pattern while meeting the safety requirement for every phase.
(2) *Add only*. The local cycle length is adjusted by adding up to a certain maximum amount per cycle.
(3) *Dwell*. The signals at each intersection stay in certain phases for up to a maximum dwell time until coordination is reached.

According to Nelson and Bullock (2000), the smooth transitioning algorithm performs the best among the three transition algorithms (i.e. smooth, add only, and dwell). This research result is in line with hardware-in-the-loop simulations carried out for the evaluation of EVSP recovery strategies in an urban corridor with four coordinated-actuated signals in Virginia (Yun et al., 2008). Simulations showed that EVSP had a significant impact on coordinated signal systems and that the smooth transitioning generally outperformed other strategies. Similar results were achieved by Obenberger and Collura (2007). Their research results showed that while efficiency of a transition strategy varied with traffic volume, the most effective transition strategy was the smooth transitioning strategy.

In search for further improvement, research reported by Mussa and Selekwa (2004) on traffic signal timing transition procedures between time-of-day (TOD) timing plans was reviewed. In this case, the starting timing plan and the ending timing plan are known. However, in the case of the EVSP, the EV entry time and the period of EV operation cannot be pre-determined. Therefore, it was observed that the signal timing transition for the EVSP cannot be modelled as an optimization process from one known signal timing plan to another.

Further literature review indicated that there is a need to develop a new EVSP system that uses ITS technologies in association with advances in control methods in order to ensure safe passage of the emergency vehicles and at the same time to minimize the impact on general traffic. The following sections of the paper cover advances made in this direction. The technologies and methods are described, but due to space limitation in this paper, only selected mathematical formulas are included. Interested readers may wish to refer to Qin (2005) for additional mathematical details.

3. Real-time control for transition 1 – from normal operation to EVSP

3.1. Design elements

For a subject intersection, the transition 1 period begins from the moment an EV is detected on one of its approaches and ends at the time the EV clears the intersection. A safety time interval is allowed in order to avoid collisions with traffic. When general traffic is moving at the operating speed of the facility, the traffic density is low and therefore ample space exists for vehicles to pull over and stop at roadside. On the other hand, vehicles in a queue during high density condition at an intersection usually do not have such an opportunity to pull over, since the space available there is very limited.

Based on the above observation, we divide vehicles into three groups, according to their states at an intersection when an approaching EV is detected (Fig. 2). (1) Vehicles in a queue at an intersection (i.e., standing queue) must pass through the intersection to clear the way for the EV, (2) vehicles moving at operating speed (i.e., moving vehicles) must pull over and stop at the roadside, and (3) vehicles moving at a speed less than the operating speed (i.e., the moving queue) should have both the opportunities to pull over or pass through the intersection.

Various sensing technologies exist for vehicle detection and also their installation design can provide vehicle speed data at intersection approaches. Please see Section 2.1 for a coverage of these technologies. From the captured data, the number of

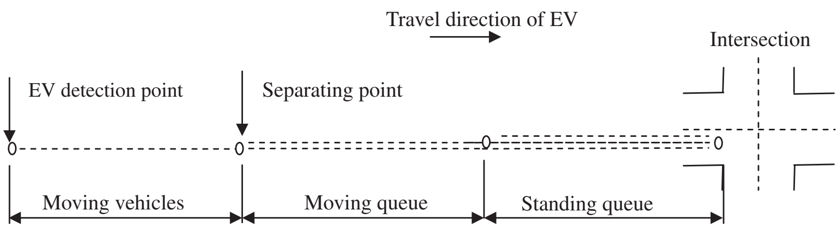

Fig. 2. Classification of vehicles at an intersection.

vehicles in each category noted in Fig. 2 (i.e., stopped or moving queues and vehicles travelling at operating speed) can be estimated. In traffic operations, the capability to identify and even predict such traffic states is becoming commonplace. Although this does not imply that technology and methods do not require further improvement, it is useful to note that much progress has already been made in developing systems for real-time traffic data capture and estimation of attributes of traffic flow (e.g. volume, density, speed, queues) (Skabardonis and Geroliminis, 2008). Many jurisdictions have tested system components and have already included these in their approved product list (APL) (e.g. Florida DOT, 2011). Depending upon the need, such products have already been implemented in many jurisdictions (e.g. Brampton, 2011).

3.2. Determination of EV detection distance

An EV approaching an intersection at its operating speed should be detected at a distance that would allow sufficient time to discharge the queue, allow a safety time interval, and to switch the green time indication to the EV approach (Fig. 3). That is, the required minimum distance of EV detection can be determined from the following relationship.

$$\text{Notification time period} \geq \text{switchover time } t_{\text{switchover}} + \text{discharge time } t_{\min} + \text{safety time interval STI}$$

The minimum distance for EV detection is calculated from the notification time period and EV operating speed. The switchover time is the time required to switch green indication from other approaches to the EV approach, and it is calculated based on the instant in the signal cycle when the signal controller receives the message of EV's approaching the intersection. The discharge time is calculated from (average queue length + two times standard deviation of queue length) on the EV approach and queue discharge speed of the EV approach. The STI is the Safety Time Interval, which must be kept between the last vehicle in the queue on the EV approach and the EV. In our simulations two seconds were used for STI.

The time period that corresponds to the EV detection distance is termed the notification time period. In order to estimate such a notification time period, a minimum distance of EV detection can be determined from the traffic flow characteristics and approach road features. In advanced actual emergency vehicle preemption systems that are now in operation, according to their design the preemption-request points can be based on average traffic conditions experienced during various time-of-day periods (e.g. peak period, shoulder period, off-peak period).

However, the authors of this paper are of the view that for realism, the stochastic nature of traffic should be taken into account in the estimation of notification time and the corresponding EV detection distance. Therefore, for improved practice, in order to ensure (i.e., at more than 97% confidence level) that in almost all traffic conditions the EV can pass through the intersection, we use (average queue length + two times the standard deviation of the queue length) in order to determine the required minimum distance of EV detection. Should abnormal traffic flow be encountered such as during highly saturated traffic conditions, the signal timing plan designed for normal operation may not be suitable to control queues below a reasonable length. Consequently, the distance of EV detection has to be modified accordingly in order to help clear gridlock. The incremental addition to the queue length equal to two times the standard deviation of the normal queue length is intended for this purpose.

As for technology, in this paper we are not endorsing a unique single technology for detecting the approaching EV. This will not be in the best interest of inducing innovation. Instead, for the benefit of the reader, we have described existing technologies that serve this purpose and are actually operational in the field. On the methodology side, we are proposing a new approach to the estimation of time when preemption request should be made. From the notification time, the corresponding distance for EV detection can be established.

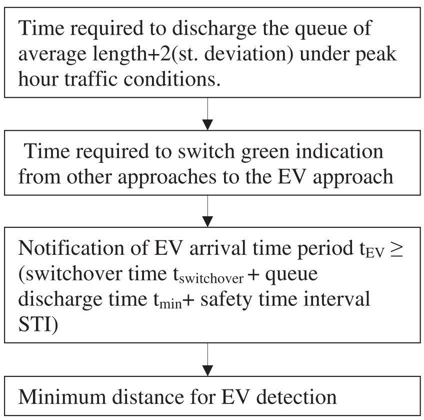

Fig. 3. EV detection distance.

3.3. Real-time control strategy for a single isolated intersection

The real-time control of the signal system must be based on the time required for the safe passage of the EV. The safe passage time includes the queue discharge time, a safety time interval, and the time required to switch green indication to the EV approach. In signal control situations that guarantee the availability of the safe passage time, if spare time is available, it can be allocated to general traffic on the cross road. This will minimize the impact of the EVSP on the general traffic. On the other hand, the green time for the EV can be extended if required.

The main elements of the real-time control algorithm for the EVSP at an intersection are shown in Fig. 4. The use of this algorithm ensures the green time needed for the safe passage of the EV and also the maximum possible green time can be allocated to the cross road. The maximum possible green time for the cross road can be determined from the following equation.

$$\begin{aligned}\text{Maximum possible green time for the cross road} &= \text{Notification time period} - (\text{switchover times} \\ &\quad + \text{queue discharge time} + \text{STI})\end{aligned}$$

The notification time period, the queue discharge time and the STI have already been defined. In the present context, the switchover time is the time required to switch green indication from the EV approach to cross roads (if green time is not needed by the EV approach and also if cross roads are not facing green when the EV is detected) and the time required to switch green indication back to the EV approach.

3.4. Real-time control strategy for a coordinated route

A difference between the coordinated route control and the single intersection control is that the arrival of vehicles at an intersection of a coordinated route is affected by the control strategy of the upstream intersection. In the case of a single intersection, no such influence is applicable. Another difference is that the EV detection distance for each intersection has to be established. If the link length between two successive intersections in a coordinated route is shorter than the distance required for EV detection for an intersection, the EV detection point for that intersection will be beyond its upstream inter-

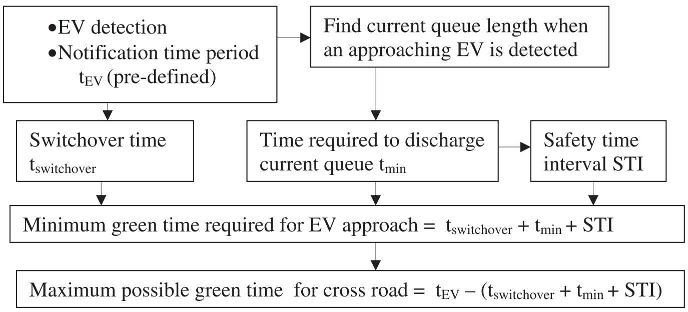

Fig. 4. Real time control for single intersection.

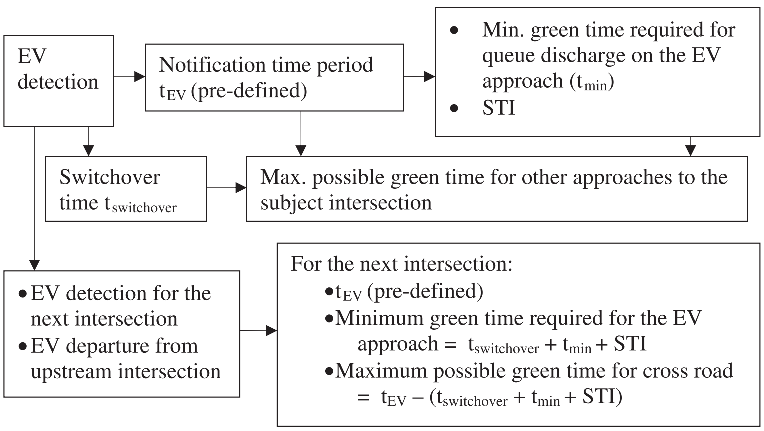

Fig. 5. Real time control for coordinated route (general case).

section. The method to determine the minimum distance of EV detection is the same as for single intersection (described above). But, the real-time control process is different due to the operation of the upstream intersection under EVSP (Fig. 5).

In addition to the equation used in the previous section to determine the possible green time for the cross road, another relationship is used to control the green time for the cross road at the subject intersection so that the net queue on the EV approach at the next intersection can be discharged before the EV reaches the next intersection.

$$q_n = q_a - q_d$$

where q_n is the net queue at the next intersection; q_a is the vehicular arrivals into the link to the next intersection from the upstream subject intersection; q_d is the queue discharged at the next intersection during the period from the instant the EV is detected to the moment the EV has just crossed the subject intersection.

4. Optimal control for transition 2 – from preemption to normal operation

4.1. Design considerations and control principle for signal transitioning

Transition 2 begins from the instant the detector confirms that the EV has cleared the intersection, and ends at the moment the controller begins the normal operation. Design considerations for this transition 2 are as follows. After the EV passes through the intersection, a safety time interval (STI) is allowed between the EV and the vehicle following it. In concept, this safety time interval is similar to the earlier ST and for this reason, the same variable name is retained. However, in this case the STI is allowed between the EV and the vehicle following it. The duration of transition should be as short as possible, and at the end of the transition the queue length on each approach to the intersection should be equal to or less than the average queue length under normal operating condition. Therefore, normal signal control strategy can be put in place as soon as possible so that the impact of EV on general traffic is minimized.

4.2. Development of the optimal control algorithm

The optimal control algorithm components are presented in Fig. 6 and the detailed formulation can be found in Qin (2005). Highlights of the control algorithm are presented in this section.

The time duration of the remaining normal cycle time (RNC) is to be found from the instant an EV just crosses an intersection to the beginning of the immediate next normal green signal phase. This establishes the recovery period RP for the optimal control process. The RP is initially selected as (RNC-STI). It is to be extended by additional signal cycle lengths for

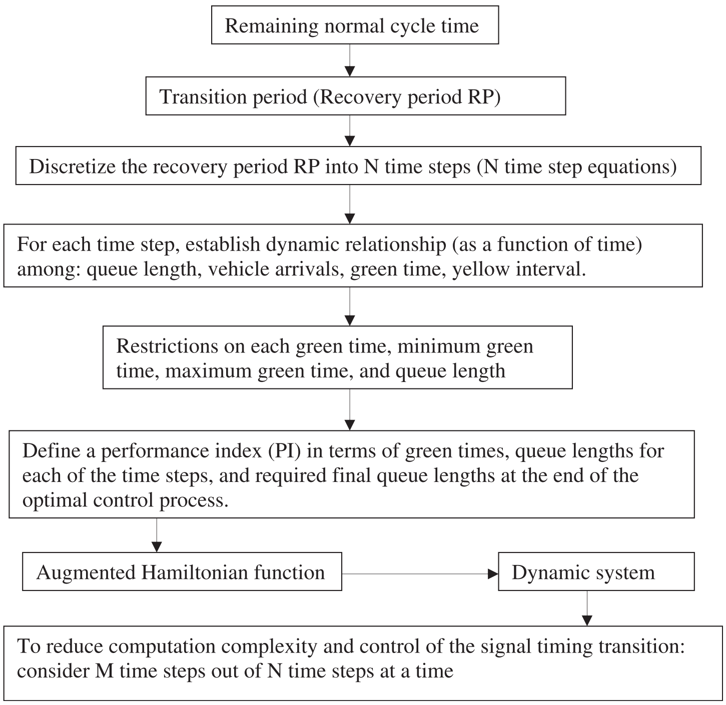

Fig. 6. Optimal control algorithm development.

normal operation if the initial RP is too short or at the end of RNC and if the queue lengths on individual approaches are longer than corresponding average values under normal operation.

The recovery period RP is discretized into N time steps (giving rise to N time step equations), and each time step consists of green times, yellow intervals, and all red intervals for individual approaches. The time duration for each time step is fixed, and green times for individual approaches are variable and are to be determined by the optimal control algorithm. A switchover during a time step will introduce an entire yellow interval and the corresponding all red interval into this time step because of safety consideration. If there is no switchover during a time step, there will be no yellow and all red intervals. The optimal control algorithm will determine whether there is any switchover or not during a time step.

For each time step, restrictions are formulated on each green time, minimum green time, maximum green time, and queue length. A dynamic relationship is established (as a function of time) among queue lengths, vehicular arrivals, green times, and yellow intervals.

$$Q(i+1) = Q(i) + A(i) - S_g^T G(i) - S_y^T \Delta(i) Y$$

where $Q(i)$ are queue lengths during ith time step on individual approaches; $A(i)$ are the number of vehicle arrivals during ith time step on individual approaches; $G(i)$ are green times during ith time step for individual approaches; Y are yellow times for individual approaches (assume they are the same for all time steps); S_g are saturation discharge rates for green time on individual approaches; S_y are saturation discharge rate for yellow time on individual approaches; $\Delta(i)$ are 0 or 1 for individual approaches depending on if there is switchover during ith time step and to be determined dynamically according to traffic condition at the intersection.

A performance index (PI) is defined in terms of green times, queue length for each time step, and required final queue lengths at the end of the optimal control process. In the PI, different weighting matrices are used to apply different weights to terminal state (final queue lengths), intermediate states (queue lengths at the end of individual intermediate time steps), and control variables (green times for individual time steps).

The performance index (PI) is defined as

$$J = \Psi(N+1, X_{N+1}) + 0.5\sum_{i=1}^{N}[X^T(i)RX(i) + U^T(i)SU(i)]$$

where $\Psi(N+1, X_{N+1})$ is a function of the final time $(N+1)$ and corresponding state (queue lengths) at the final time $X(_{N+1})$; $X(i)$ are normalized queue lengths during ith time step on individual approaches at the subject intersection; $U(i)$ are normalized green times during ith time step for main and side roads, respectively; R and S are weighting matrices for $X(i)$ and $U(i)$, respectively.

An augmented Hamiltonian function is constructed using the PI, queue length function, time step equation, and all the constraints on green times and queue lengths.

$$\begin{aligned} H = {} & 0.5[X^T(i)RX(i) + U^T(i)SU(i)] + \nabla(i)F1\{A(i), U(i), \Delta(i)\} + \sigma(i)F2\{U(i), \Delta(i)\} - \Phi_1(i)U(i) - \Phi_2(i)F3\{U(i), Umin\} \\ & + \Phi_3(i)F4\{U(i), Umax\} - \Phi_4 X(i) + \Phi_5\{X(i) - Xmax\} \end{aligned}$$

where $F1\{A(i), U(i), \Delta(i)\}$ is the queue length function for ith time step; $F2\{U(i), \Delta(i)\}$ is the time step equation for ith time step; $F3\{U(i), Umin\}$ is the minimum continuous green time constraint; $F4\{U(i), Umax\}$ is the maximum continuous green time constraint; $Xmax$ are maximum normalized queue lengths allowed on individual approaches; $\Lambda(i)$, $\sigma(i)$, Φ_1, Φ_2, Φ_3, Φ_4, and Φ_5 are Lagrangian multipliers associated with queue length function F1, time step equation $F1$, non-negative green time constraint, minimum continuous green time constraint; maximum continuous green time constraint, non-negative queue length constraint, and maximum queue length constraint.

Then, a dynamic system is established by deducing the first order necessary conditions for the augmented Hamiltonian function, and the solution to the dynamic system will be the optimal control strategy for the recovery process from the EVSP to normal signal operation.

The dynamic system cannot be solved directly because of the interrelationship between signal sequences of greens, yellows and all reds in successive time intervals. A two-phase algorithm is proposed to solve the dynamic system. The first phase is a relaxation process in which inequality constraints and the relationship between successive signal sequences are neglected, and a low bound of the solution to the original optimal control problem is deduced. Inequality constraints and the relationship between successive signal sequences are considered in the second phase of the two-phase algorithm. The second phase is a stepwise search strategy. All the possibilities of successive signal sequences will be generated, and then the stepwise search strategy checks all the sequences for feasibility. From all the feasible options, the optimal one is selected to control traffic signals.

In order to reduce computation complexity and control, in the signal timing transition in a real-time mode, only M time steps out of the total N time steps are considered at a time. After one M-step model is solved, only those optimal control parameters of the first time step within the M steps are implemented. The next M-step model will begin with the second time step in the last M-step model. This mathematical problem solving technique is especially useful in situations where a large number of total time steps are needed for the recovery process from EVSP to normal operation. Fig. 7 shows the process for determining the optimal control variables.

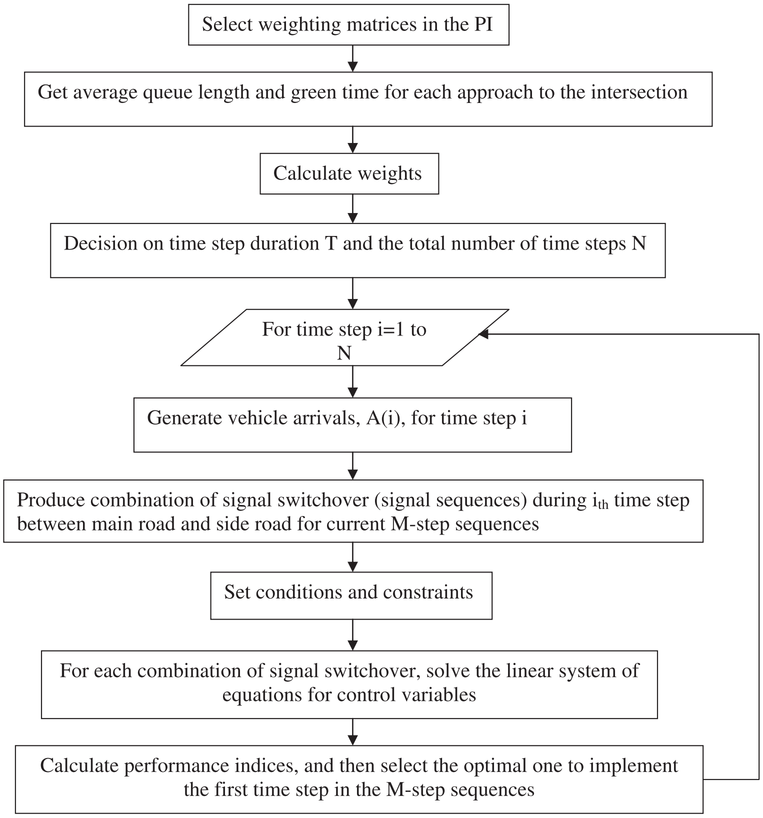

Fig. 7. Procedure for determination of optimal control variables.

5. Simulation and comparison of control strategies for single intersection

Software development environment, MATLAB (The Mathworks Inc., 2003), was used for numerical simulation in this research. Due to space limitations, only highlights of simulations and analyses are included in this paper and details can be found in Qin (2005).

5.1. Intersection layout and traffic parameters

In general, signal timing plans for normal operation can be pre-timed, traffic-actuated, or adaptive. For our research, their differences will affect only the control performances before the EVSP is carried out. To focus on the control of EVSP and without losing its applicability to other control strategies, we adopted the pre-timed plan for normal operation. The Webster's method was used to determine the signal timing. The layout of an intersection and related traffic data are shown in Fig. 8. The number of lanes on each approach can be one, two, or more than two. However, all the lanes on each approach are in one lane group. By using the traffic data and signal control parameters, 20 cycles were simulated and queue lengths for each approach were found.

For the base case (normal operation), the following signal timing were used. Cycle time = 108 s; green time = 60 s for main road and 40 s for side road; yellow = 3 s; all red = 1 s; Degrees of saturation for the base case were 0.51, 0.21, 0.41, and 0.33 for approaches 1, 2, 3, and 4, respectively. In these base conditions, the degrees of saturation were the same for all the scenarios simulated and traffic signal timings were for normal operation only because other control strategies were used for EVSP. However, it should be pointed out here that for the study of the impact of traffic volume on control efficiency of the proposed strategies (as discussed in Section 8.1), scenarios with different combinations of degree of saturation were tested. In those simulations, the degrees of saturation ranged from 0.54 to 1.08 on approach 1 (main road) and 0.27 to 1.08 on approach 2 (side road).

5.2. Simulation of control strategies for transition 1

5.2.1. Determination of EV detection distance

As discussed previously, when determining the minimum distance of EV detection away from the intersection, we used (average queue length + two times standard deviation) as the queue length so as to ensure that in almost all traffic situations

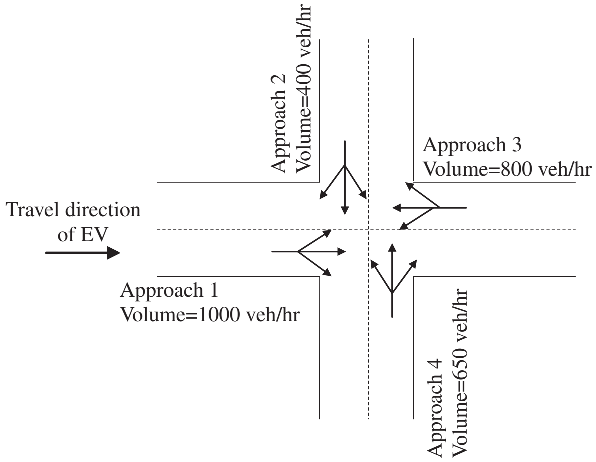

Fig. 8. Single intersection layout and related traffic volumes.

the EV can pass through the intersection. The queue length for every approach was determined. The longest switchover time was found according to the state of traffic indications when the EV was detected on the way to the intersection. Based on the simulation results of normal operation, we found the EV detection distances for all approaches. These were applied in the following simulations and analysis.

5.2.2. Cases of EV arrival from the main road

Six EVSP scenarios were defined and six runs for each EVSP scenario were simulated. The EV entered the system from approach 1 at the beginning, middle of green interval, beginning of yellow interval, beginning of red interval for the main road, and beginning, middle of green interval for side road, respectively. Fifty nine seconds were used for the real time control transitioning. In order to compare the effectiveness of the real-time control strategy with those of existing systems, the fixed held time algorithm for transition 1 was selected as reference in this research. The held time for the fixed time transitioning on approach 1 was fixed at t_{f1} = 50 and t_{f2} = 30 s, respectively. Simulation results are summarized in Table 1.

Four measures of effectiveness were used to assess control strategies: (1) "More time needed" is additional time over the transition period and it is needed to clear the queue ahead of an EV. If it is greater than 0, it means that the transition period is not long enough to clear the queue, and the EV has to stop or reduce operating speed. Therefore the signal control strategy fails to serve the EVSP operation. (2) "Spare time" is the portion of green time between the instant the queue ahead of the EV clears the intersection and the moment the EV reaches the same intersection. Because no vehicle can make use of this period, the shorter the spare time, the better the control efficiency. (3) "Green time for cross road" is the portion of the transition period that is not needed for safe EV operation and therefore it can be allocated as green time for the cross road. It is applicable only to the real-time control strategy because the fixed held time control strategy always gives green to EV during the whole transition period. (4) "Queue length" is measured at the end of the transition period.

In terms of failure numbers, while the real-time control strategy successfully dealt with every scenario, the EVSP failed one time and seven times under the 50-s and the 30-s fixed held time control strategies, respectively. It means that under the two fixed held time control strategies, the EV had to stop or reduce speed at the intersection before the queues ahead of it cleared the intersection.

By dynamically allotting green time to the side road that is not needed for the main road, our real-time control algorithm can minimize the impact of the EVSP on the side road. We can see from results presented in Table 1 that the real-time control strategy had almost no spare time. Overall, it reduced the average spare time to only 0.9 s. Under the fixed held time of 50 s, the spare time was 29.6 s. In the case of 30 s fixed time strategy, the spare time was 13.3 s.

Using average green time for side road as a measure during transition 1, an overall average of 31.5 s was extracted and allotted to the side road by the real time strategy. This compares favourably with 0 s for the fixed held time strategy. Under

Table 1
Simulation results for transition 1 (EV from the main road).

Control strategy	Fixed time t_f = 50 (s)	Fixed time t_f = 30 (s)	Real-time t_r = 59 (s)
Failure #	1	7	0
Spare time (s)	29.6	13.3	0.9
Green time for cross road (s)	N/A	N/A	31.5
Queue length (veh)	11.6	8.6	7.8

the real-time control, the developed algorithm was successful in reducing the average queue for all scenarios and approaches to 7.8 vehicles. The corresponding queue lengths were 11.6 and 8.6 vehicles under 50-s and 30-s fixed held time control strategies, respectively. This is due to more efficient allotment of green time between the main road and the side road. It should be noted that the queue length is not rounded to whole numbers since we are interested in a comparative analysis of control scenarios.

It is useful to look at the queue on individual approaches shown in Table 2. To make sure that the EV crosses the intersection without delay, the real time control strategy used longer time for transition 1 than the fixed time control strategy. The adverse effect was that the real time control strategy resulted in longer queue on the main road (approaches 1 and 3) than in the case of the fixed time control strategy. On the other hand, because of the green time for cross road the real time control strategy reduced the queue on the side road (approaches 2 and 4). For average queue over the main road and the side road, the real time control strategy outperformed the fixed time control strategy.

When looking at both spare time and average queue length, the fixed time transitioning had much higher spare time than the proposed strategy (29.6 and 13.3 s for 50-s and 30-s transitioning vs. 0.9 s for the proposed real time control strategy), but the effect on average queue length was modest (11.6 and 8.6 vehicles for 50-s and 30-s transitioning vs. 7.8 s for the proposed real time control strategy). While the effect of the proposed strategy on queue length is expected to increase with higher DOS on side road, the wastage of pre-emption time for the fixed time transitioning is the price to make sure that the EV can cross the intersection safely and without delay. As shown in Table 1, with about 30 s spare time, the 50-s fixed time transitioning still failed one time to clear the queue ahead of the EV. A shorter spare time of about 13 s was achieved by reducing the fixed time transitioning period to 30 s, but the failure number increased to seven times. The reason behind the spare time is the stochastic characteristic of traffic at the intersection. For realism, the proposed strategy attempts to make use of the stochastic characteristic and allocates green time to cross road when possible.

5.2.3. Cases of EV arrival from the side road

The EVSP scenarios and simulation runs were the same as in the case of EV arrival from the main road except when the EV entered the intersection from approach 2. Twenty three seconds were used for the real-time control transitioning. The held time for the fixed time transitioning on approach 2 was fixed at $t_{f1} = 30$ and $t_{f2} = 20$ s, respectively. Simulation results summarized in Table 3 indicate that each signal control strategy was successful in letting the EV pass through the intersection without stopping or reducing operating speed during transition 1. Similar to observation in cases for EV from main road, the real-time control strategy produced the least overall average spare time among the three control strategies. However, the overall average spare time (4.3 s) is relatively large as compared with the spare time of 0.9 s (shown in Table 1) that was experienced when the EV entered the system from the main road (approach 1) and the average transition period was longer at 59 s. This relatively higher spare time could be caused by a shorter transition period used (i.e., 23 s).

Table 3 also shows the average green time for the main road during transition 1 when the EV entered the system from the side road. For all scenarios, the real-time control strategy extracted 9.8 s in green time for the main road during transition 1. The control algorithm performance can also be assessed by the average queue length over all scenarios and approaches. The real-time control strategy demonstrated the best control result with 7.8 vehicles, compared with 10.9 vehicles and 9.4 vehicles under 30-s and 20-s fixed held time control strategies, respectively.

The queue lengths on individual approaches are summarized in Table 4. On the EV approach 2, the real time transitioning of 23 s was enough to clear the intersection for the EV and caused shorter queue than the fixed time transitioning of 30 s but longer than the fixed time transitioning of 20 s. Similar to analysis above for EV arrival from the main road, approach 4 on the EV route had longer queue for the real time transitioning than the fixed time transitioning and approaches 1 and 3 on the non-EV route had significantly shorter queue for the real time transitioning than for the fixed time transitioning.

Table 2
Average queue length (veh) for transition 1 (EV from the main road).

Control strategy	Fixed time $t_f = 50$ (s)	Fixed time $t_f = 30$ (s)	Real-time $t_r = 59$ (s)
Approach 1	16.8	10.7	19.3
Approach 2	11.1	8.8	3.4
Approach 3	0.4	0.8	3.0
Approach 4	18.2	14.2	5.6

Table 3
Simulation results for transition 1 (EV from the side road).

Control strategy	Fixed time $t_f = 30$ (s)	Fixed time $t_f = 20$ (s)	Real-time $t_r = 23$ (s)
Failure #	0	0	0
Spare time (s)	25.6	15.6	4.3
Green time for cross road (s)	N/A	N/A	9.8
Queue length (veh)	10.9	9.4	7.8

Table 4
Average queue length (veh) for transition 1 (EV from the side road).

Control strategy	Fixed time $t_f = 30$ (s)	Fixed time $t_f = 20$ (s)	Real-time $t_r = 23$ (s)
Approach 1	26.8	23.0	18.3
Approach 2	3.9	2.6	3.0
Approach 3	12.9	10.6	3.7
Approach 4	0.7	1.5	5.6

Table 5
Simulation results for transition 2.

Control strategy		Smooth control	Optimal control
EV from approach 1 (main road)	Recovery time (s)	162	79.8
	Queue length (veh)	12.4	9.6
EV from approach 2 (side road)	Recovery time (s)	180	69.2
	Queue length (veh)	9.5	8.1

5.3. Simulation of control strategies for transition 2

In order to compare the effectiveness of our optimal control strategy with that of the smooth control strategy over an obvious and simple base, we choose fixed held time ($t_f = 50$ s for the EV from the main road or $t_f = 20$ s for the EV from side road) strategy as used for transition 1. It means that queue lengths on individual approaches at the beginning of transition 2 are those formed at the end of fixed held time control strategy with 50 or 20 s held time on main road and side road, respectively. Since the objective of the optimal control strategy developed in this research is to minimize the queue lengths at the intersection during a shortest possible time after the EV has crossed the intersection, recovery time and queue length are used as measures of effectiveness for the simulation. Table 5 summarizes simulation results under the smooth transitioning and the optimal control strategy.

Table 5 shows that the optimal control strategy is better than the smooth transitioning option since it has resulted in the average recovery time of 79.8 s vs. 162 s for the case of the EV from the main road and 69.2 vs. 180 s for the EV from the side road. Considering another control performance index, the average queue length, the optimal control strategy again outperformed the smooth transitioning. The optimal control strategy allotted green time to each road only when green time was most needed according to current traffic condition. Because of the random nature of vehicle arrivals at the intersection, the optimal control strategy could successfully allocate green time to each road in a dynamic manner. The optimal control algorithm reduced overall average queue to 9.6 and 8.1 vehicles as compared to 12.4 and 9.5 vehicles under the smooth control algorithm for the EV from main road and side road, respectively.

6. Simulation and comparison of control strategies for coordinated route

To go beyond the isolated single intersection case, the control of a coordinated route was simulated in order to study the effectiveness of the strategies developed in this research. Once again, results of the real time control strategy were compared with fixed held time approach for transition 1. Likewise, in transition 2 simulations, the effectiveness of the optimal control algorithm was checked against the smooth transitioning control method.

6.1. Layout of subject coordinated route and traffic parameters

Fig. 9 presents the layout of the subject coordinated route. There are four signalized intersections, 1, 2, 3, and 4, along the route, and the EV is going to travel from intersection 1 to 4. The distance between intersections i and j is denoted by L_{ij}. The vehicular volumes at an intersection i are represented by V_{iE}, V_{iN}, V_{iS}, and V_{iW} for eastbound, northbound, southbound, and westbound approaches, respectively.

Simulation was first conducted under normal traffic control operation in order to obtain control parameters for the real-time control method and the optimal control algorithm. Here, we used the same normal signal control parameters as for the single intersection. The signal offset between two intersections was simply determined by using the quotient of link length and general vehicle operating speed. After 20 cycles were simulated, the average queue lengths under normal operation were calculated.

6.2. Control strategies for transition 1

For comparison, a 50-s fixed held time control strategy was simulated first as reference, followed by the simulation of the real-time control strategy. In the real-time control, the average queue length + two times standard deviation, found under

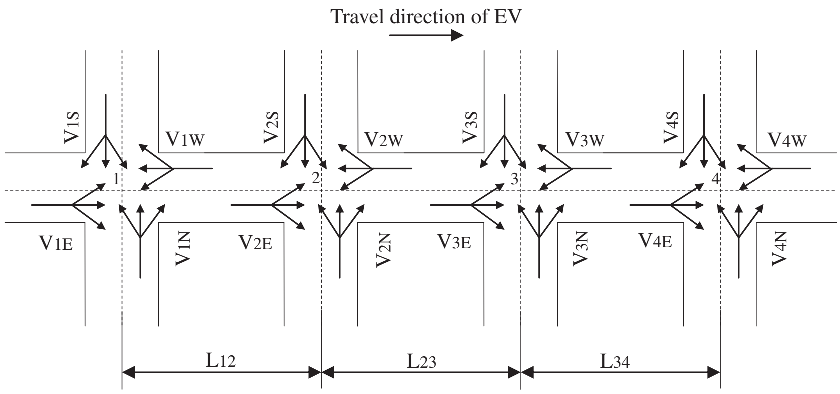

Fig. 9. Layout of subject coordinated route.

normal operation, was used to determine EV detection distances away from intersections. It should be noted that since link lengths between two successive intersections are shorter than corresponding required EV detection distances, the EV detection point for an intersection is beyond its upstream intersection. In advanced EV preemption systems, it is common practice to send preemption request in this manner in order to help clear queues.

The EVSP scenarios were defined and simulated and results were averaged over the four EV scenarios (i.e., scenarios of EV entry) and the six cycles simulated (Table 6). These results show that both the 50-s fixed held time control and the real-time control were successful in clearing the queue at each intersection before the EV crossed the intersection. It means that the EV crossed the route smoothly and no delay occurred during the EVSP. Table 6 also shows average spare times on each eastbound approach along the route. The spare time noted in the table indicates that the real-time control wasted little green time, and an average of only 1.3 s was not used either by the EV route or by the cross road at each intersection. On the other hand, the fixed held time control strategy incurred much longer spare times at all intersections and the average spare time at each intersection was 41 s. It means that an average of only 9 s was actually used to clear queue at an intersection for each EVSP occurrence.

Green time for the side road is only applicable to the real-time control strategy since the fixed held time control strategy always gives green to EV route during the whole transition duration. We can see from Table 6 that the real-time control strategy extracted an average of 27.5 s to clear queues on the side roads at each intersection during each EVSP occurrence. In terms of queue length, over all the four intersections, the real-time control strategy reduced average queue per intersection to 5.5 from 7.5 vehicles under the fixed held time control strategy, i.e., a 26.6% (=(7.5–5.5)/7.5 = 0.266) rise in control efficiency.

Average queue lengths on the main road and the side road are summarized in Table 7. Similar to analysis for individual intersection scenarios, the real time control strategy caused longer queue on the main road but much shorter queue on the side road than the fixed time control strategy.

6.3. Control strategies for transition 2

We first obtained simulation results under the smooth control strategy as reference, and then the optimal control strategy was applied to the same traffic situations to show its merits. Similar to the single intersection control, in order to focus on the comparison between these two control strategies, a 50-s fixed held time control strategy for transition 1 was used to produce queue lengths on each approach in the subject route at the end of transition 1. From here, control strategies for transition 2 take the responsibility to revert the traffic signal back to normal operation in a quick and efficient manner.

In the simulation of the coordinated route control, we used the same parameters and algorithms of smooth transitioning and optimal control that were used for the single intersection case, except average queue lengths for normal operation were different. These were obtained from the simulation of the coordinated route control and used in the optimal control algo-

Table 6
Coordinated route simulation results for transition 1.

Control strategy	Fixed time t_f = 50 (s)	Real-time t_r = varies
Failure #	0	0
Spare time (s)	41.0	1.3
Green time for side road (s)	N/A	27.5
Queue length (veh)	7.5	5.5

Note: Results were averaged over the four intersections along the subject route.

Table 7
Average queue length (veh) on the coordinated route for transition 1.

Control strategy	Normal operation	Fixed time $t_f = 50$ (s)	Real-time t_r = varies
Main road	12	5.7	8.5
Side road	9.4	9.3	2.6

Note: The queue lengths were averaged over the four intersections.

Table 8
Coordinated route simulation results for transition 2.

Control strategy	Smooth transitioning	Optimal transitioning
Recovery time (s)	189	68.5
Queue length (veh)	7.9	5.3

Note: Results are averaged over the four intersections along the subject route.

rithm as control parameters. In the first three scenarios, for the EV route, the EV entered the route at the beginning, middle, and end of green interval, respectively. In the fourth scenario, the EV entered in the middle of the red interval for the EV route. In order to consider the randomness of traffic situations, six occurrences for each EVSP scenario were simulated. These were carried out separately and then results were averaged. Table 8 summarizes simulation results for route control.

From Table 8, we can infer that the optimal control strategy needed only 36.2% (=68.5/189) of recovery time under the smooth control algorithm to get the traffic signal back to normal operation. While the optimal control strategy obviously outperformed the smooth control algorithm in terms of recovery time, we could not reach a firm conclusion until another factor for the assessment of control algorithm, namely average queue length, was studied. Over the whole route, the optimal control algorithm produced an average queue of 5.3 vehicles on each approach compared with 7.9 vehicles under smooth transitioning. This suggests a 32.9% (i.e., (7.9–5.3)/7.9 = 0.329) rise in control efficiency.

7. Guidelines on weighting matrices

Simulations were carried out in order to study the impact of weighting matrices on the optimal control strategy. Weighting matrices are used to weight the elements in the performance index differently, and they include P' for free final state, R for intermediate states, and S for control variables. In previous simulations, we used identities as weighting matrices in the optimal control algorithm for transition 2. In this section, the impact of different weighting matrices on control efficiency is noted.

A set of combinations of weighting matrices was selected for simulation. The optimal control strategy with each combination of weighting matrices was applied to traffic conditions with different degrees of saturation, ranging from 0.54 to 1.08 on the EV approach and 0.27 to 1.08 on the cross road. The simulation results are summarized here and the detailed results can be found in Qin (2005).

For a stable behaviour of the optimal control algorithm and short mean queue length, weighting matrix combinations should be selected as follows. (a) Weighing matrix S for control variables should be less than or equal to weighting matrix P' for final states and weighting matrix R for intermediate states. (b) When traffic volumes are very light at an intersection, R should be greater than P'.

8. Robustness tests

Further simulations were carried out in order to test the robustness of the developed strategies and associated methods. Two types of investigations were performed: (1) impact of traffic volume on control efficiency, and (2) control efficiency for multiple EVSP occurrences. Although an overview of results of these tests is presented below, due to space limitation only queue length findings for multiple EVSPs are presented in Table 9.

8.1. Impact of traffic volume on control efficiency

The simplest four-leg intersection with two-phase signal system (Fig. 10) was used again for these simulations. All lanes on each approach were considered to be in one lane group. Approaches 1 and 2 were critical approaches and their volumes determined the signal timing plan and the EVSP efficiency. Traffic volume on an opposing approach was set at 0.8 times volume on its corresponding critical approach. The EV route was from approach 1 to approach 3.

Scenarios with different degrees of saturation were tested. The degrees of saturation ranged from 0.54 to 1.08 on approach 1 and 0.27 to 1.08 on approach 2. Simulation results show that the real-time control strategy failed in two cases, each for a separate scenario. Therefore, this means one failure per scenario. Since there were 24 test cases (four EV occurrences

Table 9
Queue lengths for multiple EVSPs.

Scenario	Queue over all approaches			
	Transition 1		Transition 2	
Base case	q_N (veh)	51.4	q_N (veh)	51.4
EVSP scenario 1	q_R (veh)	42.02	q_O (veh)	31.86
	q_R/q_N (%)	82	q_O/q_N (%)	62
EVSP scenario 2	q_R (veh)	39.07	q_O (veh)	30.06
	q_R/q_N (%)	76	q_O/q_N (%)	58
EVSP scenario 3	q_R (veh)	51.21	q_O (veh)	46.79
	q_R/q_N (%)	100	q_O/q_N (%)	91
EVSP scenario 4	q_R (veh)	53.62	q_O (veh)	49.48
	q_R/q_N (%)	104	q_O/q_N (%)	96

Notes: (1) q_N (veh) = average queue length under normal operation. (2). q_R (veh) = average queue length after real-time control. (3). q_O (veh) = average queue length after optimal control.

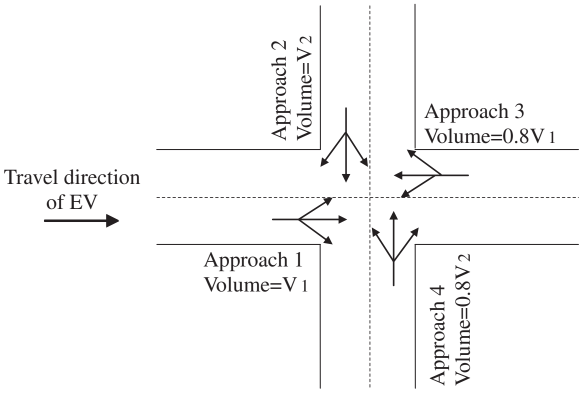

Fig. 10. Critical approaches and relative traffic volumes.

and six cycles for each EV occurrence) for each scenario, the failure rate was less than 5% (1/24 = 4.2%). This finding implies that the real-time control strategy is still reliable. After the EV crossed the intersection, the transition 2 under the optimal control began to get the signal control back to normal operation. On the cross road, average queue lengths were controlled below the corresponding values under normal operation. At the end of the optimal control process, slightly longer average queues than corresponding values under normal operation were observed only on the EV approach in scenarios that featured oversaturated traffic (i.e., volume/capacity ratio of 1.08) on the approach.

8.2. Control efficiency for multiple EVSP occurrences

If two successive EVs request signal preemptions with a long time interval between such requests, they can be treated as two separate signal preemption occurrences, and control strategies discussed previously are still applicable to this situation. However, if multiple EVSPs occur within a short time interval, there exists the possibility that another EV can approach an intersection before the control strategies complete the process of signal transition for a preceding EV. Therefore, the control strategies were enhanced for such a circumstance.

A brief explanation of enhancement is provided here and the detailed formulation can be found in Qin (2005). When two successive EVs request signal preemption within a short time interval, three scenarios apply, based on the time headway Δt, between the preceding EV, EV(1), and the following EV, EV(2). These scenarios relate to the transition period of real-time control for EV(1), TP(1), and the recovery period for EV(1), RP(1).

(1) Δt < TP(1): EV(2) enters the EVSP system before EV(1) crosses the intersection.

There is no optimal control (transition 2) for EV(1) and the real-time control (transition 1) for EV(2) starts immediately after EV(1) crosses the intersection.

(2) TP(1) $\leqslant \Delta$t < TP(1) + RP(1): EV(2) enters the EVSP system after EV(1) has crossed the intersection but before the optimal control process (transition 2) for EV(1) is completed.

The recovery period for EV(1) is stopped and the real-time control for EV(2) starts when EV(2) is detected.

(3) $\Delta t \geqslant \mathrm{TP}(1) + \mathrm{RP}(1)$: EV(2) enters the EVSP system after transition 1 and transition 2 have been completed for EV(1).

The EVSP operation for EV(1) is an isolated EVSP occurrence and control algorithms are the same as described previously.

The four-leg intersection with two-phase signal system was used in this test. The intersection layout, traffic volumes, pretimed signal plan for normal operation, and average queue lengths under normal operation were the same as for the isolated EVSP occurrence at individual intersection control. Only the real-time control strategy and the optimal control strategy were different.

EVs were generated on approach 1 with the heaviest traffic among the four approaches. Three EVSPs at closely timed intervals were simulated. For each headway and each EV entry time, six different periods were used to consider the fluctuation in general traffic at the intersection. Simulation results were then averaged over the four entry times and the six cycles for each headway EVSP scenario. The queue length results are presented in Table 9.

The following indicators of control efficiency were studied: number of failures for control strategy, average green time for side road, average spare time, and average queue lengths after the implementation of real-time control. The results were favourable. For example, as shown in Table 9, the real-time control algorithm for multiple EVSP occurrences kept the overall relative queue lengths below or about 100% in four EVSP scenarios. These were 82%, 76%, 100%, and 104% for scenario 1, 2, 3, and 4, respectively.

Under the optimal control strategy for multiple EVSP occurrences, the overall relative queue lengths after the recovery period were controlled at 62%, 58%, 91%, and 96% for scenario 1, 2, 3, and 4, respectively. These results are not surprising because these are in accordance with the goal of the optimal control algorithm (i.e., minimization of the overall relative queue length instead of individual approaches at an intersection).

9. Conclusions and field implementation consideration

Simulation results provide the evidence that the real-time control strategy for transition 1 is superior to fixed held time control strategy, and the optimal control strategy for transition 2 gives better results than the smooth control strategy. The applicability of these technology-assisted strategies and their associated methods to an isolated single intersection as well as intersections of a coordinated route was successfully demonstrated in the simulation test bed.

The real-time control strategy for transition 1 ensures that the EV can pass through the intersection at its operating speed. A safety time interval is allowed to ensure that safety is not compromised. Additionally, while allocating sufficient green time for queue clearance under prevailing traffic conditions, it has the capability to reduce queues on the cross road.

For the recovery period (i.e., transition 2), the optimal control strategy proposed in this research handles conflicting demands from the main and the side roads very well. The success of the optimal control strategy results from the randomness of vehicle arrivals at the intersection. The fluctuation in traffic makes it possible for the optimal control strategy to allocate green time to each road dynamically only when it is beneficial to do so. The technology-assisted algorithm developed in this research makes the optimal control feasible.

The study of the effect of different weighting matrices on the optimal control strategy produced useful guidelines for the application of the optimal control algorithm. The results of the two robustness tests were favourable. It was demonstrated that the proposed control strategies are applicable to different traffic conditions up to and slightly over saturated level. Likewise, these can handle multiple EVSP occurrences as well as single EVSP occurrence.

The results obtained from proof of concept research reported here are promising and suggest that the next step is a demonstration study in an actual traffic network. The developed software used in the simulation test bed can be programmed into the logic of a modern controller. The ITS technologies and associated methods required for EV detection, the estimation of EV notification time, detection distance, and traffic flow characteristics are commonly available as a part of advanced signal control installations. A communication link can connect these with the EVSP controller.

As a part of the suggested field implementation study, the following problems have to be addressed. (a) The real time control strategy assumes that there is ample space beyond the intersection so that vehicles in a queue at the intersection can find space to pull over after they cross the intersection. If there is no space available beyond the intersection, such as in gridlock traffic conditions, the real-time control strategy will not be able to clear the way for the EV by allotting green time to the queue. Other control strategies have to be devised to deal with these situations. (b) The distance of EV detection is determined by using the statistical values of peak period queue length as a base. If the signal timing plan for normal operation is not suitable for traffic conditions or it is not able to control queues below a reasonable length, especially in highly over-saturated traffic conditions, long queues may form on the EV approach. Consequently, the distance of EV detection will be far away from the intersection, which will make it a challenge to estimate EV and other vehicles' arrival time at the intersection. Although it is common practice to send preemption request to multiple intersections in highly saturated traffic conditions, further research will be required for refining this practice by applying the developed methodology. The objective of further research will be to develop predictive tools with the potential to produce reliable estimates of queue formation and dissemination.

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