MOUNTAIN-PLAINS CONSORTIUM

MPC 23-503 | K. Yao and S. Chen

FRAMEWORK OF ADAPTIVE INTERSECTION TRAFFIC CONTROL STRATEGY FOR URBAN TRAFFIC NETWORK SUBJECTED TO DISRUPTIONS

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
MPC-679		

4. Title and Subtitle	5. Report Date
Framework of Adaptive Intersection Traffic Control Strategy for Urban Traffic Network Subjected to Disruptions	August 2023
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Suren Chen Kaisen Yao	MPC 23-503
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Colorado State University 1372 Campus Delivery Fort Collins, CO 80523	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Mountain-Plains Consortium North Dakota State University PO Box 6050, Fargo, ND 58108	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Supported by a grant from the US DOT, University Transportation Centers Program

16. Abstract

Mitigating congestion at urban traffic system intersections following major hazards and incidents is a crucial step to maximize the evacuation, rescue and recovery efficiency and prevent a hazard from turning into a disaster. An optimized traffic signal design strategy can effectively contribute to maintaining an efficient traffic system operation despite various disruptions. Most existing studies focus on static and generic congestion scenarios during the recovery stage rather than realistic time-progressive scenarios covering the entire process following a disruption. An adaptive traffic signal control strategy in response to traffic disruptions at a single intersection is proposed by covering both the incident and recovery stages. Dynamic phase selection (DPS) technology is applied to adjust the traffic signal control plan adaptively during the incident stage, while the queue length dissipation (QLD) algorithm is adopted to carry out optimal green time calculation during the recovery stage. The proposed methodology is demonstrated by considering disruptions caused by several typical vehicle crashes at intersections. The proposed DPS+QLD traffic signal strategy is found to improve the resiliency of a typical intersection against disruptions by clearing the queue faster, reducing overall traffic loss time, and maintaining stable mobility with superior performance over conventional fixed and actuated traffic signal plans.

17. Key Word	18. Distribution Statement
adaptive control, traffic signal control systems, urban highways	Public distribution

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	26	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Framework of Adaptive Intersection Traffic Control Strategy for Urban Traffic Network Subjected to Disruptions

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Acknowledgement

The funds for this study were provided by the United States Department of Transportation to the Mountain-Plains Consortium (MPC).

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ABSTRACT[1]

Mitigating congestion at urban traffic system intersections following major hazards and incidents is a crucial step to maximize the evacuation, rescue and recovery efficiency and prevent a hazard from turning into a disaster. An optimized traffic signal design strategy can effectively contribute to maintaining an efficient traffic system operation despite various disruptions. Most existing studies focus on static and generic congestion scenarios during the recovery stage rather than realistic time-progressive scenarios covering the entire process following a disruption. An adaptive traffic signal control strategy in response to traffic disruptions at a single intersection is proposed by covering both the incident and recovery stages. Dynamic phase selection (DPS) technology is applied to adjust the traffic signal control plan adaptively during the incident stage, while the queue length dissipation (QLD) algorithm is adopted to carry out optimal green time calculation during the recovery stage. The proposed methodology is demonstrated by considering disruptions caused by several typical vehicle crashes at intersections. The proposed DPS+QLD traffic signal strategy is found to improve the resiliency of a typical intersection against disruptions by clearing the queue faster, reducing overall traffic loss time, and maintaining stable mobility with superior performance over conventional fixed and actuated traffic signal plans.

[1] This report is based on the contents from the published journal paper: Yao, K. and Chen, S. (2022). “Resilience-based adaptive traffic signal strategy against disruption at single intersection,” *ASCE J. of Transportation Engineering, Part A,* 148(5): 04022018, http://dx.doi.org/10.1061/JTEPBS.0000671.

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Intelligent technology has become a key solution to traffic control in urban cities to mitigate congestion and reduce delay (Andronov and Leverents, 2018). Intelligent traffic signal control efforts primarily focus on applying different algorithms to meet the needs of traffic safety and efficiency with the data from monitoring cameras, road sensors, existence detectors, and other devices. (Pandit et al., 2013). Typical modes of operation for traffic signals include pre-timed (fixed time) and actuated operations. Despite being straightforward and easy to coordinate between intersections, pretimed operation is more suitable for close intersections with constant traffic volumes; it lacks flexibility to adjust with varying traffic demands and environments. Actuated operation, on the other hand, can adjust phase durations and sequences by detecting real-time traffic conditions, such as prolonging or shortening phase durations and skipping a phase based on traffic demand. As a result, actuated operation does not have a fixed cycle length because of not always displaying a complete sequence and duration of a cycle, and therefore it is hard to coordinate among intersections.

Over the past decade, resilience design has been a trending topic to maintain functional and sustainable infrastructures under disruptive scenarios caused by various hazards or incidents. A traffic system, as the backbone of any modern city, plays a key role in improving mobility, safety, and efficiency of not only people and goods, but also the functionality of other interdependent infrastructures (e.g., energy, communication, and water) as well as the whole community (Zou and Chen, 2019). Transportation systems are vulnerable to various disruptions caused by excessive traffic demands, inclement natural environments, man-made hazards, and other incidents. Vehicle crashes, for example, are the most common type of traffic disruptions responsible for most non-recurring congestion and delay during daily operations (Wang et al., 2020). Especially at urban traffic system intersections, vehicle crashes often result in long queue lengths so that considerable time resources have been wasted due to induced congestions (Fei et al., 2017).

Traffic signal designs are critical to traffic safety and efficiency at intersections during day-to-day service, including normal or heavy traffic scenarios (Gartner et al., 1995). Significant research efforts have been made to study signal timing optimization and incident detection techniques to mitigate recurring traffic congestion during rush hours. An improved automatic traffic incident detection technique using vehicle to infrastructure (V2I) communication was proposed to receive the incident information in time for the following optimizations (Sheikh et al., 2020). Discrete dynamic optimization models for optimal cycle length and green time allocation were evaluated to identify the most appropriate design to deal with congested traffic scenarios (Chang et. al., 2000). In recent years, some emerging research efforts have investigated intersection signal designs for non-recurrent congestion caused by traffic crashes. A game theory-based controller approach for the estimation of aggressive driving behaviors and traffic incident detection was used to reduce traffic accidents and improve traffic system safety (Sheikh et al., 2021). A cell transmission model for a signalized intersection was developed for different congestion evacuation schemes (He et al., 2017). GPS data for vehicle information were utilized for a global network model to evaluate traffic conditions with matrix factorization and clustering methods during emergency recovery (Han et al., 2019). A signal timing optimization model using queue length as the penalty value has been developed under traffic incident scenarios, in which a heuristic algorithm (simulated annealing algorithm) was adopted (Wang et al., 2020). Most of the existing studies focused on congestion mitigation during the crash recovery stage rather than the entire process following a crash occurrence. In addition, existing studies all assumed simplified and generic congestion scenarios without looking at the realistic time-progressive nature of congestion developments following crashes at intersections. In fact, different types of crashes may occur at intersections, which will cause a different nature and severity of congestions to deal with. As a result, the optimal traffic control strategy in response to disruptions is rarely generic and should be adaptively adjusted with specific incident and congestion information. Furthermore, there are usually more traffic crashes when driving environments deteriorate before, during, and after some natural or man-made hazards and major incidents. During those critical moments, every second counts to mitigate the congestion, maximize the evacuation and rescue efficiency, save more lives, and prevent a hazard from becoming a disaster. Therefore, it is critical to have a more adaptive and smarter traffic control strategy covering not just the static and genetic congestion scenarios during the recovery stage, but also the dynamic scenarios covering the entire process, including both emergency response and long-term recovery following a disruptive event.

Dynamic phase selection (DPS) has been successfully adopted in some fully actuated traffic signal controls to skip unused phases when there is no call for service, so the green time can be allocated to other phases. As a result, the traffic signal control process would be more intelligent and adaptive by reducing unused waiting time and improving overall efficiency (Eom & Kim, 2020). With DPS, traffic signal control at intersections becomes self-organized in response to different traffic needs during normal traffic conditions (Zubillaga et al., 2014). Despite its great potential, little effort has been reported in terms of adopting DPS on traffic signal designs during disrupted traffic scenarios.

1.2 Organization of Report

This paper proposes an adaptive traffic signal control strategy in response to traffic disruptions at a typical intersection by integrating microscopic traffic simulation, traffic signal design with DPS technology, the queue length dissipation (QLD) algorithm, and resilience modeling concept. After the methodology is introduced, disruptions caused by typical vehicle crashes at intersections, including rear-end, angle-impact, and opposite-direction (left-turn vs. through) crashes, are specifically studied. The proposed resilience-based strategy is applied to adjust the traffic signal control plan adaptively covering the period immediately following the incident until congestion is fully recovered to normal conditions by aiming to achieve optimal traffic efficiency and resilience outcome. With the adaptive strategy, the sequence of signal phases is adjusted based on the near real-time optimization and calculation of optimal signal timing without fixed cycle length and phase sequence, which may vary from cycle to cycle based on real-time traffic conditions.

The report is composed of three sections. Section 1 introduces background information and literature review results related to the present study. In Section 2, the proposed adaptive traffic strategy at a single intersection is introduced and demonstrated. Section 3 summarizes the findings from the report, followed by some discussion.

2. METHODOLOGY OF ADAPTIVE INTERSECTION CONTROL

2.1 SUMO-based Microscopic Traffic Simulation Platform at a Single Intersection

The proposed strategy is developed based on the popular microscopic traffic simulation tool "Simulation of Urban Mobility" (SUMO). SUMO is an open source, highly portable, and continuous road traffic simulation package designed to handle large road networks. For applications at intersections, SUMO not only offers microscopic-scale traffic flow simulation, but also accommodates various types of vehicles, roads, and traffic lights with an excellent graphical user interface and interoperability with other applications at runtime (Lopez et al., 2018). The microscopic-scale traffic modeling with SUMO at a typical intersection provides reliable and accurate traffic performance information, which will lead to optimized traffic signal designs. Figure 1 shows the typical movement of a four-way intersection, of which phases 1, 3, 5, and 7 are for left-turn movements and phases 2, 4, 6, and 8 are for through and right-turn movements at different directions. Normally, phases 1, 2, 5 and 6 are used for major roads with high and consistent traffic volumes. The other phases are primarily for minor roads with low traffic volumes. As shown later, dynamic phase selection (DSP) will be applied based on the phase movements depicted in Figure 2.1.

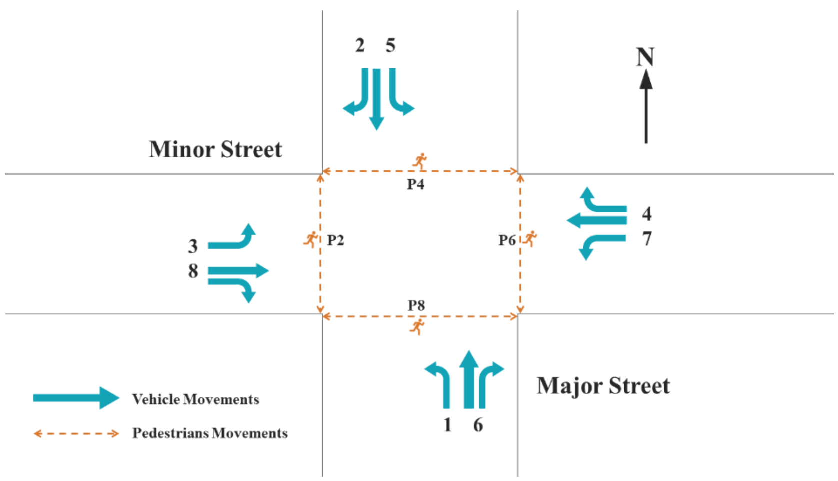

Figure 2.1 Intersection phase movements

2.2 Adaptive Traffic Signal Strategy in Response to Disruptions at Intersection

The adaptive traffic signal strategy is developed for the two stages following an incident: the incident stage covers the time between the incident occurrence and the time when the rescue or emergency response efforts are finished; the recovery stage covers the duration following the incident stage until the traffic has returned to normal. Basically, DPS is adopted to skip unnecessary phases during the incident stage, and the queue length dissipation (QLD) algorithm is used to dissipate the queue length at crash lanes once the recovery stage starts. This traffic signal strategy process is called the DPS+QLD plan and the overall workflow is shown as follows:

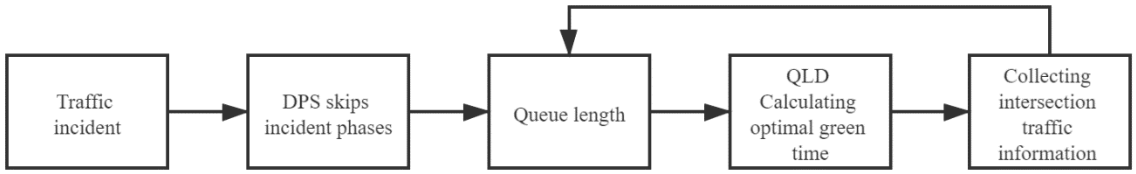

Figure 2.2 Adaptive traffic flow strategy workflow

As shown in Figure 2.2, during the first stage immediately following the incident, DPS is used for skipping unused phases of the blocked approach due to incidents to save the time loss of the intersection operation. In the second stage, when the incident is cleared, queue length information is collected to calculate the optimal signal timing to dissipate the queue as soon as possible. When the maximum green time g_{max} is reached, the controller will move to the next phase to avoid redundant green time causing long queue lengths on other approaches. After the first cycle, queue length information at the end of the red time is collected again for the following signal timing calculations. In the following sections, both DPS and QLD algorithms focusing on incident and recovery stages are introduced in detail.

2.2.1 Dynamic Phase Selection (DPS) Algorithm: Immediately Following Disruption

After a traffic incident has occurred, typically very few or no vehicle from the approach with the incident uses the green light. Therefore, such a period can be allocated to other phases to improve the mobility of the remaining approaches to avoid long queues. DPS can adaptively choose the best phase sequence of a cycle to make traffic more efficient with the help of monitoring detectors. Starting at the major road movement, the next phase is chosen dynamically based on all candidate phase options with the following algorithm (Zubillaga et. al., 2014):

1. Compute the priority for each phase given in the list of indices (the sequence of potential phases that will be used for the next phase following the current one) for next possible movements as "next" attribute. Priority is made according to the number of active detectors for that phase. A detector is deemed "active" when either of the following conditions is met:
   a) The time gap between consecutive vehicles is shorter than the threshold.
   b) Vehicle existence is detected after the signal being turned to red from the last cycle.
2. The current phase is available to continue implicitly if its maximum duration (MaxDur) is not reached and the current phase detector gets a bonus priority.
3. The phase with the highest priority is used for the next cycle over other possible movements.
4. If no traffic is detected, the phases will follow the default cycle defined by the first value in the "next" attribute.
5. If a particular phase needs to remain active for a no-traffic scenario, it must have a high maximum duration value and its index number is on the "next" list.
6. If the time that an active detector was not served exceeds the preset time threshold, such a detector will receive bonus priority for the time that was not served.

Based on the algorithm introduced above, as shown in Figure 2.3, DPS can choose the next phase according to the real-time traffic situation, which was originally used to skip unnecessary phases for minor roads if there is no vehicle approaching the green light. Similar algorithms will be applied to skip the phases for the movement at the incident location with disruptions and reallocate the green time to other phases to make the remaining parts of the intersection work efficiently. Using a rear-end crash as an example, vehicles from the approach where the crash occurred cannot pass the intersection because of traffic disruption. Therefore, the through phase of this approach is skipped by moving onto the next available phase. The skipped phase will not be used again until the crash is cleared and vehicles resume movement on the affected lanes. In such a case, a certain amount of time could be saved for better movement of the intersection for other phases.

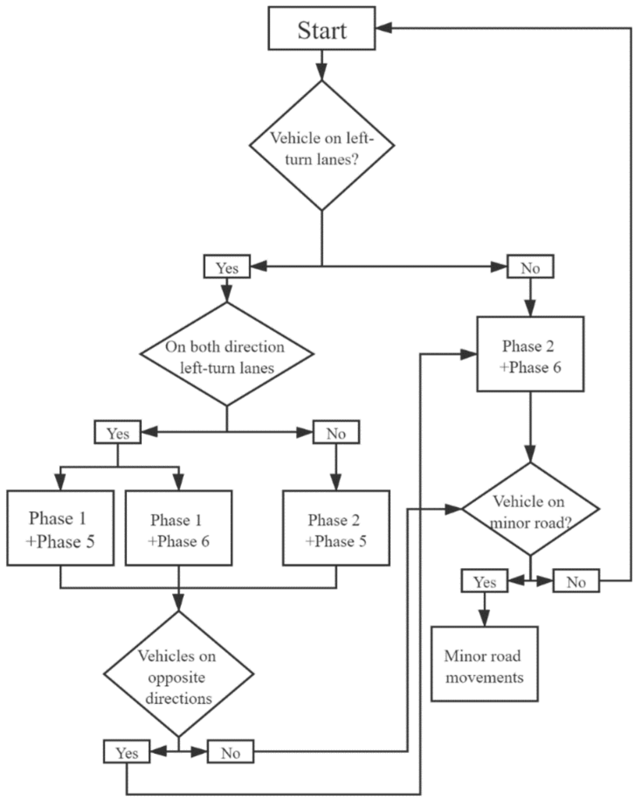

Figure 2.3 DPS algorithm flowchart

2.2.2 Queue Length Dissipation (QLD) Algorithm: Recovery Process

After the incident (e.g., crash) is cleared, queued-up vehicles on the approach with the incident need longer green time for queue dissipation. However, the required green time should be calculated based on the queue lengths of not only the approach experiencing the incident, but also other intersection approaches at the same time to avoid causing additional congestion in other directions. Therefore, the maximum green time g_{max} should be applied to balance the green time allocations among different approaches. Based on the analytical method by Akçelik (1994, 1995a), the average green time and cycle length of an actuated controller adopt a fixed unit extension setting by assuming the arrival headway follows the bunched exponential distribution (Cowan, 1978). Existing vehicles remaining in front of the green light are defined as bunched vehicles while new arriving vehicles are defined as free vehicles. Different proportions of bunched and free vehicles define the minimum and maximum green time, g_{min} and g_{max}, respectively. The green extension time e_g is set based on the queue length at the red-light ending time point, and the phase change does not happen during the saturated portion of the green period.

The green time g can be estimated by (Akçelik, 1994):

$$g = g_s + e_g \quad (1)$$

where g is the green time and g_s is the saturated portion of the green period; e_g is the extension time if the phase change happens after the queue clearance period.

The green time range is set as:

$$g_{min} < g < g_{max} \quad (2)$$

The saturation portion of the green period is calculated by:

$$g_s = \frac{f_q yr}{1-y} \quad (3)$$

where:

f_q	=	queue length calibration factor to allow for variance in queue clearance time.
r	=	effective red time for the phase.
y	=	q/S, ratio of arrival flow rate (q) to saturation flow rate (S).

The average extension time except for the saturated portion can be calculated by (Cowan, 1978):

$$e_g = n_g h_g + e_t \quad (4)$$

where:

n_g	=	average number of arrivals before phase change after queue clearance.
h_g	=	average headway of arrivals before phase change after queue clearance.
e_t	=	terminating time at phase change (is often equal to the unit extension time U).

For most cases, $e_t = U$ and Equation 4 becomes:

$$e_g = \frac{1}{q} + \left(\frac{\Delta}{\varphi} + \frac{1}{q}\right) e^{q(U-\Delta)} \quad (5)$$

where:

q	=	arrival flow rate.
Δ	=	minimum headway.
φ	=	proportion of free vehicle.
U	=	unit extension time (1s).

The green light distribution for the approach with the incident follows the rules considering the queue lengths of other approaches (Cowan, 1978):

$$g = \begin{cases} g_s + e_g, & for\ g_s < g_{sj} \\ g_s, & for\ g_s > g_{sj} \end{cases} \tag{6}$$

where g_{sj}=the saturation portion of the green period of the j^{th} direction and j= 1,2,3.

To facilitate resilience-based traffic signal design, two indexes are introduced. One is the travel time index (TTI), which is to characterize the mobility of the intersection immediately following the disruption with the ratio between the travel time of any candidate signal plan with disruption and the intersection travel time without disruption. The other is queue length index (QLI), which is to define the efficiency of the traffic signal performance during the post-disruption recovery process. The definitions of TTI and QLI are outlined below:

$$TTI(t) = \frac{Travel\ time\ with\ disruption}{Travel\ time\ without\ disruption} \tag{7}$$

$$QLI(t) = \frac{Queue\ length\ with\ disruption}{Queue\ length\ without\ disruption} \tag{8}$$

2.3 Traffic Signal Study Following Crashes at Intersection

The proposed methodology can be applied to study disruptive traffic scenarios from different incidents. In the following section, several typical traffic crashes are studied as incidents at the prototype intersection as a demonstration.

2.3.1 Study Area

Fort Collins, Colorado, is a typical moderate-size urban community in the western part of the country, which is chosen as the prototype study region due to its representative nature and data availability. The Harmony and Timberline Road four-way intersection was selected as the study area because it is one of the most representative major intersections in the city which links two busy corridors. A microscopic traffic model of the Harmony and Timberline intersection is built with SUMO (Figure 2.4). All the intersection geometry and lane arrangements follow the actual data except for the approach lengths, which are different from the actual setting so that the simulation can accommodate various queue length scenarios. By replicating the realistic turn bay lengths, spillover and spillback situations during post-crash periods can be appropriately modeled. The actual intersection fixed traffic signal plan is modeled as the baseline scenario and the monitored traffic volume data provided by the City of Fort Collins are adopted. The basic intersection and traffic data are shown in Table 2.1 and Table 2.2, respectively.

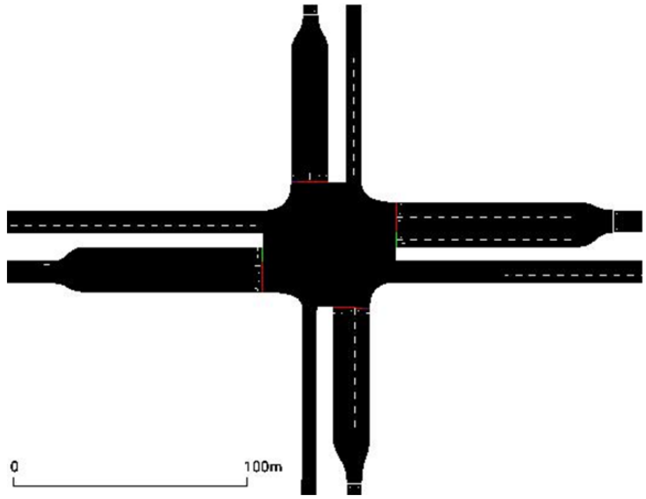

Figure 2.4 Intersection modeling in SUMO

Table 2.1 and Table 2.2 provide the basic information and parameters to simulate the intersection with SUMO based on the real-life data. In Table 2.1, the length is approximately the through lane length from different directions to the intersection; turn pocket length is the length of left-turn and right-turn lanes; the numbers of the left-turn lanes and right-turn lanes are the same for different directions; the through lane numbers in southbound and northbound directions are 2; and the through lane numbers in eastbound and westbound directions are 3. Table 2.2 lists the actual traffic volumes coming from different directions through the intersection during the PM peak hour of a typical weekday, and the free flow speed adopts the respective speed limits for all the directions.

Table 2.1 Intersection layout

	Southbound	Northbound	Eastbound	Westbound
Length(m)	500	500	1000	1000
Turn pocket length (m)	55	54	77	78
Through lane	2	2	3	3
Left-turn lane	2	2	2	2
Right-turn lane	1	1	1	1

Table 2.2 Traffic volume information

	Southbound	Northbound	Eastbound	Westbound
Traffic volume (vph)	1490	1315	2280	2064
Left-turn traffic volume (vph)	328	408	410	289
Through traffic volume (vph)	775	710	1528	1507
Right-turn traffic volume (vph)	387	197	342	268
Free flow speed (m/s)	17.88	17.88	20.12	20.12

2.3.2 Crash Types Investigated in This Study

To demonstrate the proposed adaptive strategy under incidents, three different vehicle crash types are studied: rear-end, angle-impact, and opposite-direction (left-turn vs. through) crashes. Note that occasionally partial closure rather than full closure of the approach may be implemented after the crash occurs. However, partial closure involves many factors with high uncertainties, which are hard to quantify and validate with current data. To avoid possibly ambiguous findings and maintain a reasonable research scope by focusing on the worst-case scenarios, the entire approach with the crash occurrence is assumed to be closed in this study. For the opposite-direction crash scenario, left-turn lanes at the eastbound approach and all the through lanes at the westbound approach are closed.

The PM peak hour traffic in a weekday is chosen as the simulation scenario and the typical actual traffic volume data are adopted. The total simulation period is 3,600s, which can be divided into three parts: 1) initialization part (900s) – the vehicles start getting into the network and the simulation results become stable and remain in equilibrium; 2) crash part (900s) – the crash has happened and the affected approach is closed when vehicles start queueing up; and 3) clearance part (1,800s) – the crash has been cleared, and the remaining queue starts to be dissipated. No pedestrian is considered in this study and the impact of emergency vehicles on the traffic movement is ignored.

To compare the proposed traffic signal design with traditional traffic signal plans, both fixed and actuated traffic signal control plans are modeled for the same intersection under the same conditions. A fixed traffic signal plan uses constant green time and unchanged phase sequence, which follow the actual intersection traffic signal design. In this study, to provide an easy and fair comparison without introducing too many variables, the actuated traffic signal control is limited to adjusting the green time based on traffic volumes, but not the phase sequences. The green durations for the fixed traffic signal and the ranges for the actuated traffic signal plan for all phases are shown in Table 2.3.

Table 2.3 Signal time for fixed and actuated traffic signal control plans

	Eastbound and Westbound Left Turn	Eastbound and Westbound Through	Northbound and Southbound Left Turn	Northbound and Southbound Through
Fixed traffic signal	15s	38s	14s	33s
Actuated traffic signal	5-20s	15-60s	5-20s	15-60s

2.3.2.1 Rear-end Crash

A rear-end crash is assumed to happen at the westbound approach through lanes (Figure 2.5). The red strip in Figure 2.5 stands for the closed segment because of the crash at the intersection. Although left-turn vehicles can theoretically pass the intersection (left turn bay is open), vehicles often quickly jam the left-turn lanes without movement due to spillover effects. Therefore, all the lanes on this approach are practically closed quickly following the crash. The intersection layout for a rear-end crash and the spillover effect are shown in Figure 2.5 and Figure 2.6:

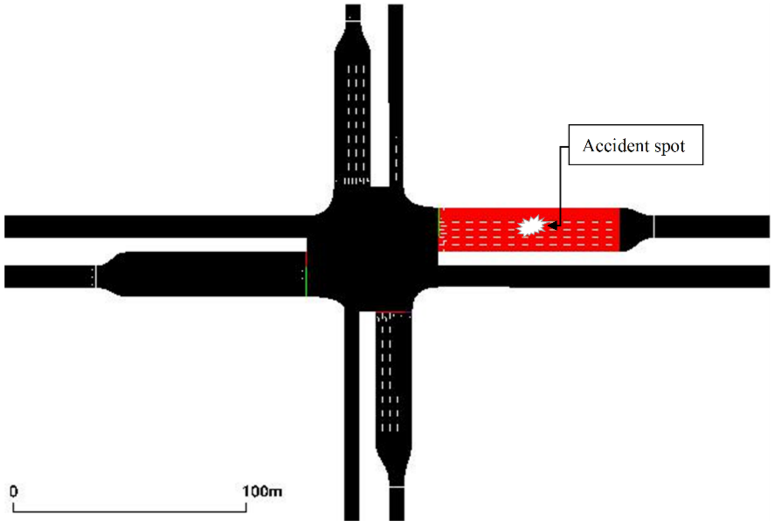

Figure 2.5 Rear end crash spot and crash segment

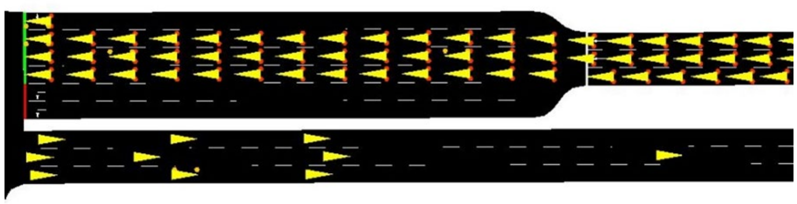

Figure 2.6 Spillover effect

2.3.2.2 Angle-impact Crash

An angle-impact crash here is about a vehicle crashing with another from different directions at an intersection (e.g., right-angle or “T-bone” collisions). In this study, the crash spot and closed segment are shown in Figure 2.7. Most parameters, such as the simulation and crash durations, remain the same as the rear-end scenario except that both the approaches of westbound and northbound traffic are closed. As compared with the rear-end scenario, an angle-impact crash may experience a longer and more complex queue, which needs to be considered for green time allocation. An optimal balance between green time and queue length of different disrupted approaches should be achieved.

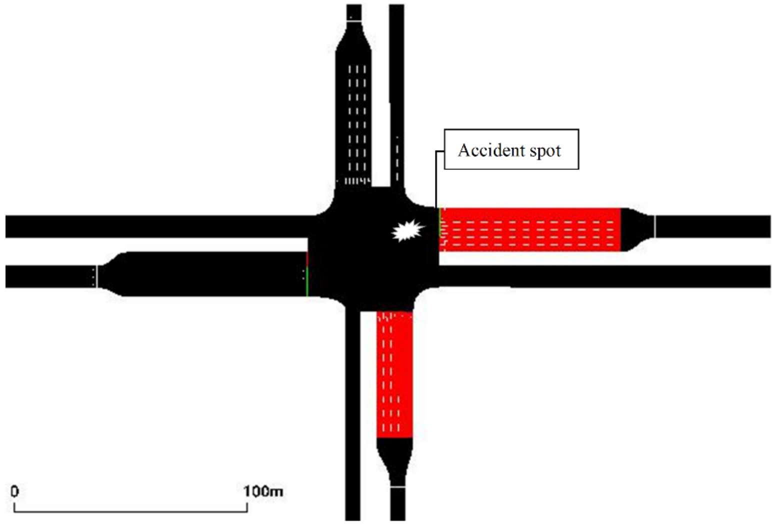

Figure 2.7 Angle-impact crash spot and closed segment

2.3.2.3 Opposite-direction Crash (Left-turn vs. Through)

An opposite-direction crash is a rare but critical crash type at the intersection with severe consequences. Unlike angle-impact crashes at intersections, it is about the conflicts between vehicles in opposite directions (e.g., left-turn vehicles vs. through vehicles from the opposite direction). The crash spot and closed segment are shown in Figures 8 and 9. In this case, the left-turn lanes of the east-bound direction and all the lanes on the west-bound direction are closed. The left-turn vehicles from the eastbound direction will be queued up, resulting in spillback effect to block the through vehicles.

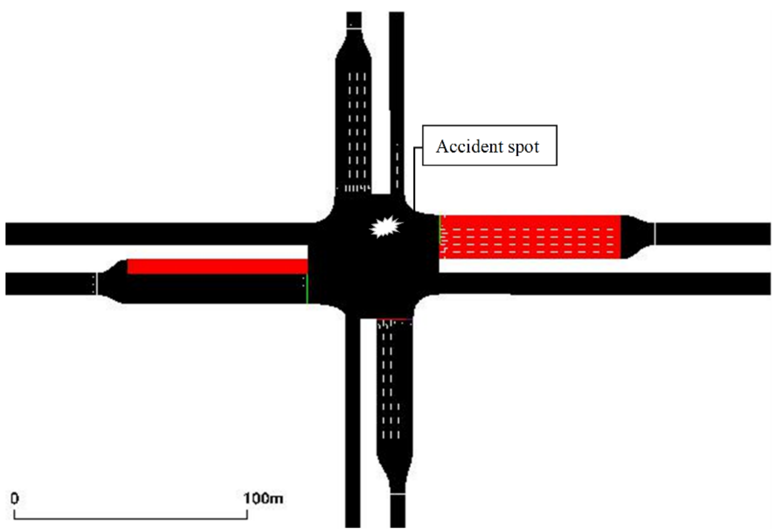

Figure 2.8 Left turn approach crash spot and closed segment

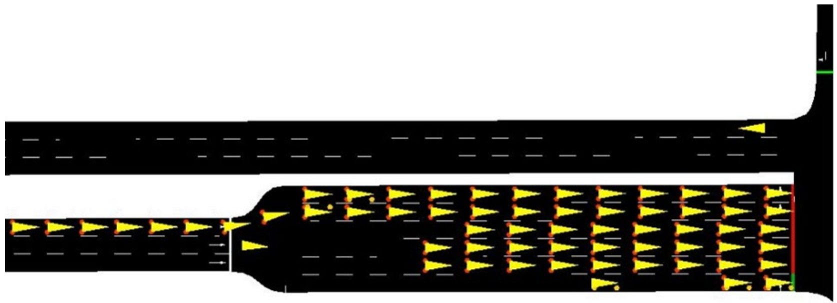

Figure 2.9 Spillback effect

2.3.3 Impact of Traffic Disruptions Caused by Crashes

Before investigating any new traffic control plan, the impact on traffic performance from crashes is studied first. A comparison is made in terms of the traffic performance between two moments: before and after the rear-end crash. Figures 2.10 and 2.11 give the results of queue lengths at the crash spot and average speed of the entire intersection. In Figure 2.10, the results of the recovery stage are listed (i.e., 30 minutes after the simulation starts). The queue length at the crash spot dramatically increases to over 350 m right before the recovery stage. During the recovery stage, the queue length is eventually restored to a normal situation about 45 minutes after the simulation has started.

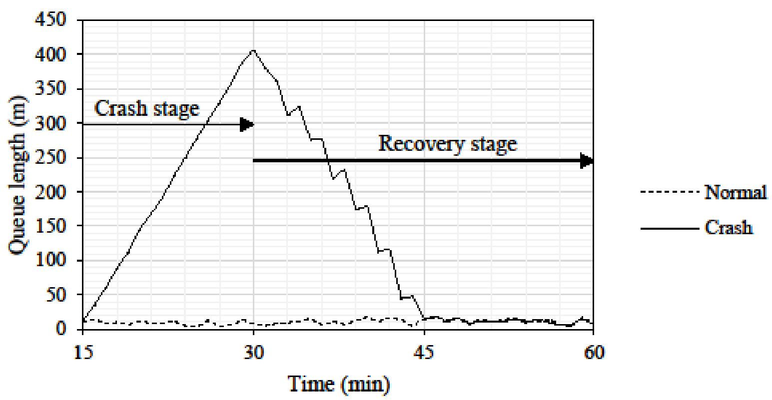

Figure 2.10 Queue length at crash spot

As shown in Figure 2.11, the average speed of the intersection quickly dropped to around 2 m/s within about 15 minutes after the crash occurred. It will take about another 20 minutes to return to normal average speed. Apparently, significant delay at the intersection would occur as the result of the crash, which can be critical during emergencies. To achieve the best performance, it is clear that the signal optimization work needs to be conducted for both the incident (crash) stage immediately following the disruption and the recovery stage.

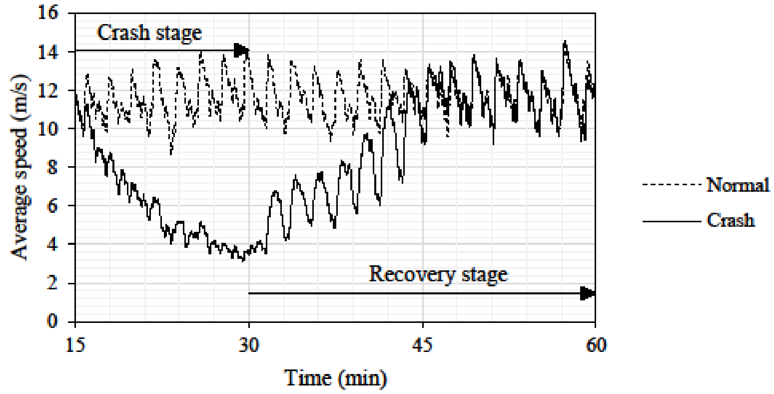

Figure 2.11 Intersection average speed

2.3.4 Comparison of three traffic signal control plans

In the following sections, a comparison of three traffic signal control plans is made: fixed time, actuated, and the proposed DPS+QLD plans.

2.3.4.1 Rear-end Crash

Figure 2.12 shows the variation of the queue length of the approach with the crash over simulation time. The *x*-axis starts 30 minutes after the simulation starts, which corresponds to the beginning of the recovery stage when the crash site has been cleared. The initial queue QLI for this approach is 59 right before the recovery starts. The DPS+QLD signal control plan can dissipate the queue length faster than the other approaches and bring the intersection's performance back to normal in only 12 minutes. In contrast, 15 minutes and 14 minutes are, respectively, required for recovering the intersection's mobility for fixed and actuated signal controls.

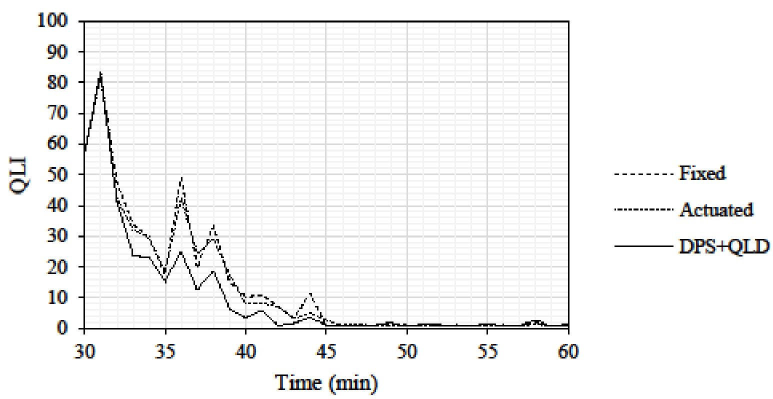

Figure 2.12 Crash approach queue length index variation for rear-end crash

Figure 2.13 represents the time loss on the westbound approach under different traffic control plans. The time loss is calculated based on the comparison of the travel time passing through the intersection with the speed limit for all traffic during the simulation. The DPS+QLD plan has a time loss of 36 seconds, which is lower than 44 seconds, and 46 seconds for the fixed and actuated traffic signal plans, respectively. Apparently, the DPS+QLD plan has the potential to not only dissipate the queue length as quickly as possible, but also optimize traffic performance on the approach directly affected by the crash.

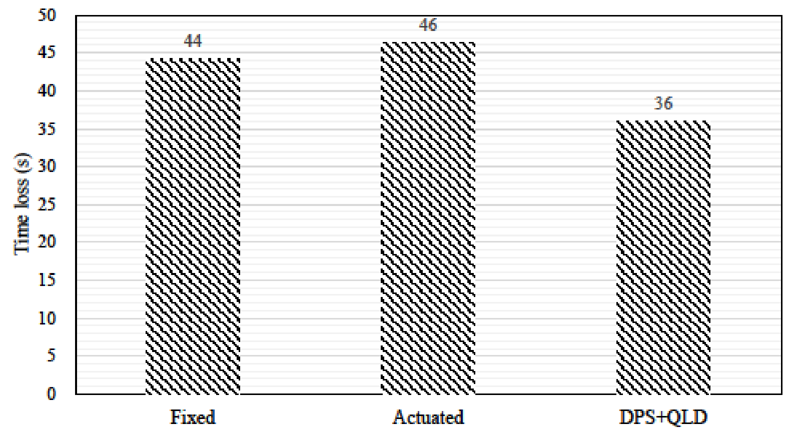

Figure 2.13 Time loss for westbound approach comparison for rear-end crash

After comparing the queue dissipation ability at the crash approach for these traffic signal control plans, it is important to study the whole intersection performance during and following the crash stage. Figure 2.14 shows the TTI of the network using different traffic signal control plans. The data are collected from the beginning of crash occurrence (900s) to the moment when the disruption is fully recovered (2,700s). During the incident (crash) stage, the DPS+QLD plan has lower travel time than those with the other two signal control plans because the phase for the crash approach is skipped and the corresponding green time is then allocated to other phases. During the recovery stage, the DPS+QLD plan also exhibits relatively lower travel time as compared with the other two strategies. Traffic efficiency using the DPS+QLD plan has been consistently improved during both crash and recovery stages for the rear-end crash scenario.

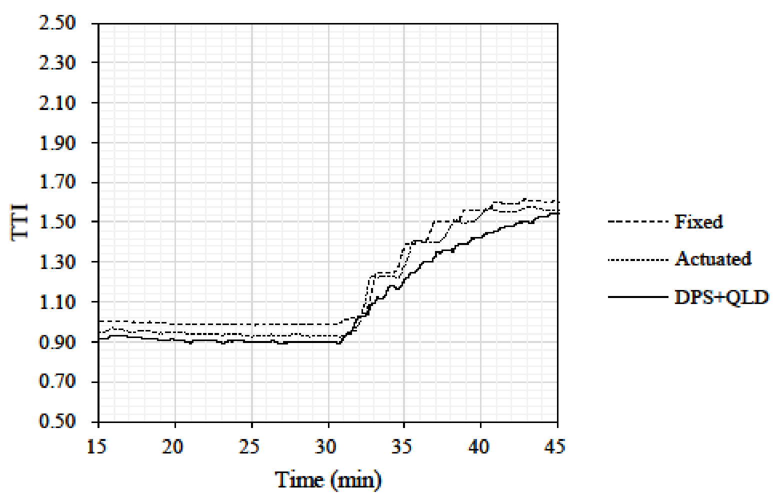

Figure 2.14 Travel time index comparison at the intersection for rear-end crash

2.3.4.2 Angle-impact Crash

Angle-impact crash scenario is studied in this section. Figures 2.15 and 2.16 show the queue length variations over time on westbound and northbound approaches, respectively. For the westbound approach, the results for DPS+QLD, fixed, and actuated traffic signal plans exhibit similar results, while the DPS+QLD plan performs only slightly better than the other two plans (13 minutes vs. 15 minutes) (Figure 2.15). A significant difference is observed in the results for the northbound approach (Figure 2.16). The DPS+QLD plan quickly reduces the queue length in about 11 minutes and maintains constant queue lengths for the remaining period of the recovery stage. In contrast, fixed and actuated traffic signal control plans will have larger queue lengths, which also vary considerably from cycle to cycle. The large fluctuations of queue lengths between cycles are not ideal from both traffic control and traffic safety perspectives.

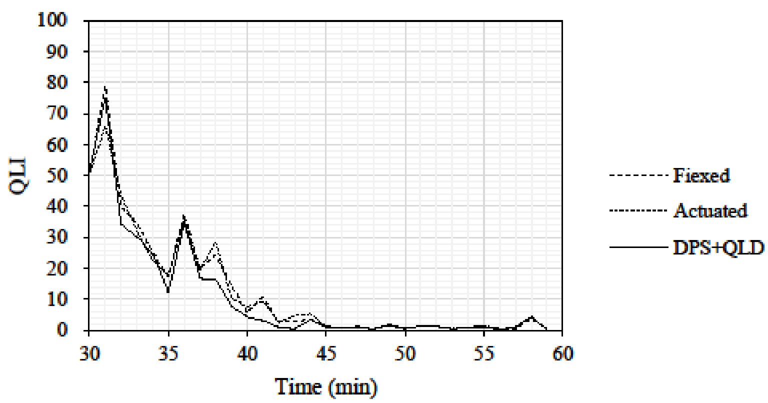

Figure 2.15 QLI for westbound approach

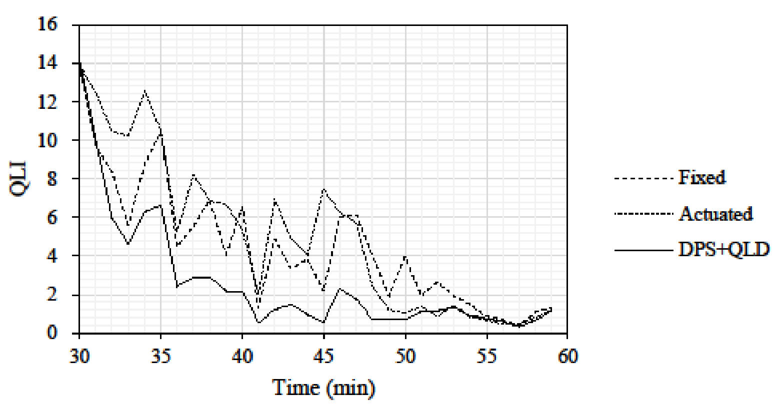

Figure 2.16 QLI for northbound approach

Figure 2.17 summarizes the time loss data for two approaches with different traffic signal plans. In addition to queue length clearance efficiency, the DPS+QLD plan also achieves superior performance in terms of time loss for the angle-impact crash scenario. The DPS+QLD plan can lead to the lowest time loss of 43s and 44s for the westbound and eastbound approaches, respectively.

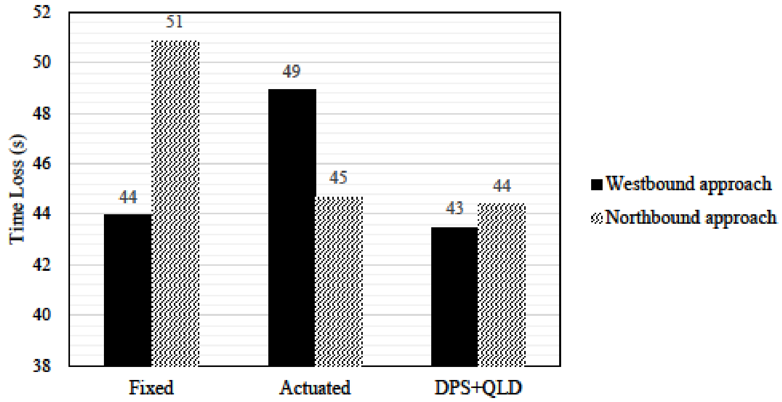

Figure 2.17 Time loss of three traffic signal strategies on two approaches for angle-impact crash

Figure 2.18 shows the TTI values over time for the three traffic signal control plans. The DPS+QLD plan is still found to have the best overall intersection performance among the three traffic signal control plans. By comparing the results in Figure 2.18 and Figure 2.14, it can be found that the advantage of DPS+QLD plan over the other two traffic signal control plans in terms of TTI for angle-impact crashes is less significant than that for rear-end crashes. During the time immediately following the incident (crash) stage, DPS+QLD plan for these 2 types of crashes have similar TTI around 0.9. However, during the recovery stage, TTI for rear-end crashes increase much slower than that for angle-impact crashes, which means the recovery speed in terms of travel time is generally lower for rear-end crashes than that for angle-impact crashes.

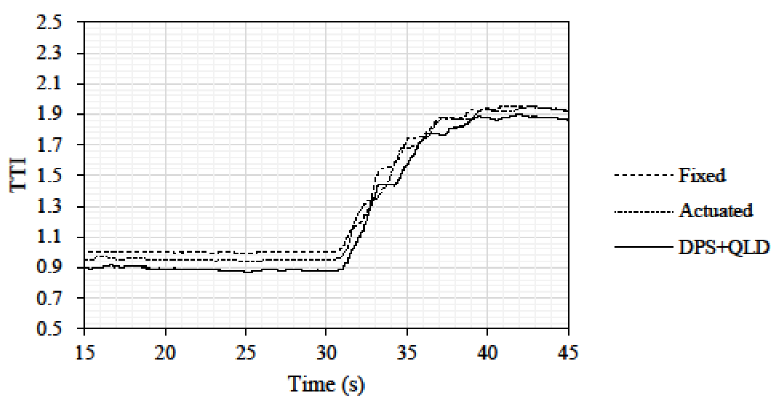

Figure 2.18 TTI of the intersection for angle-impact crash

2.3.4.3 Opposite-direction Crash (Left-turn vs. Through)

For opposite-direction crashes like left-turn movement vs. through traffic, the QLI values for the left-turn lanes are plotted in Figure 2.19 for three traffic signal design plans. Because of the phase skipping function for the DPS+QLD plan, the initial QLI of DPS+QLD plan was only 8.99, which is much smaller than those of the fixed and actuated signal control plans (both around 12.37). Such an initial advantage makes the DPS+QLD plan to dissipate the queue length in only five minutes, while the other two traffic signal control plans would take eight to 10 minutes to bring the intersection performance back to normal. The QLI results for the westbound approach are not shown here because of similarity to those of the rear-end crash scenario.

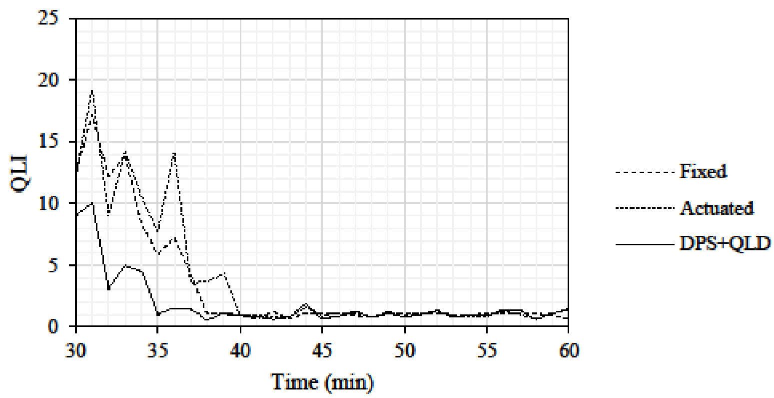

Figure 2.19 QLI comparison for left-turn lane

Figure 2.20 provides the time loss data of the left-turn lane and through lane for the three traffic signal plans over the entire simulation period. The high time loss at the left-turn lane is mainly attributed to the spillover effect that both left-turn and through vehicles are in queue. Among the three traffic signal plans, DPS+QLD is still found to be the most efficient one with the lowest time loss for both left-turn and through approaches.

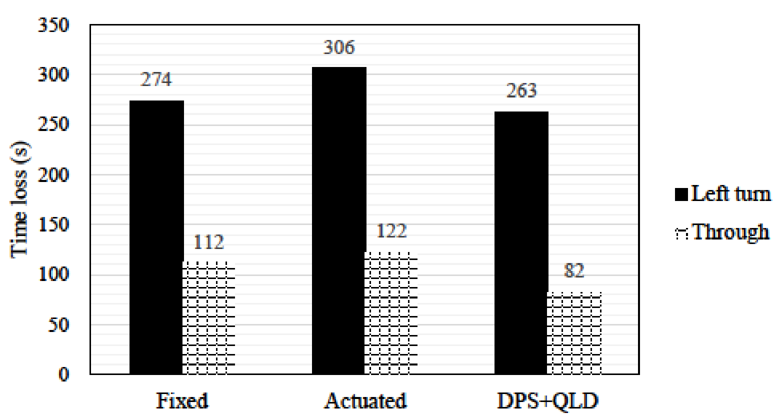

Figure 2.20 Time loss of left-turn lanes and through lanes

3. CONCLUSIONS

This study has proposed a new adaptive traffic signal strategy integrating dynamic phase selection (DPS) and queue length dissipation (QLD) for disrupted scenarios with incidents at a single intersection. DPS technique is applied to skip unused phases during the incident period to avoid time waste, which may not only shorten the queue lengths at the impacted approaches, but also improve the intersection's overall traffic performance. Optimal green time is further decided by applying a QLD signal timing optimization algorithm. The proposed DPS+QLD traffic signal design plan aims to improve the resiliency of a typical intersection against disruptions caused by hazards or incidents by clearing the queue faster, reducing overall traffic loss time, and recover intersection mobility quickly. Depending on the specific traffic disruption scenarios, there may be some time periods during which no vehicle remains on some specific lanes or approaches of the intersection due to the disruption. Since no call of service is needed for that phase during certain time periods, DPS can skip the unused phase and reallocate green time to other phases to shorten the entire cycle length. Such an adaptive adjustment on traffic signal control may not only shorten the queue length near the disrupted area, but also help mitigate overall congestion at the intersection. For disruptions caused by various hazards or other emergency events, the relief on traffic delay at major intersections can greatly support emergency response and recovery efforts to potentially save more lives and build a more resilient traffic network.

During the demonstrative study, a typical major intersection at the City of Fort Collins was modeled using the actual weekday PM peak-hour traffic data. Three typical crash types were studied as disruption scenarios: rear-end, angle-impact, and opposite direction crashes. The results of queue length variation and time loss of the impacted approaches over time were studied by establishing two resilience-based indexes, QLI and TTI. The cumulative travel time results over the simulation period and for the whole intersection were studied. Comparative investigations of the three traffic signal control plans (i.e., fixed, adaptive, and DPS+QLD plans) suggest that the proposed traffic signal control plan DPS+QLD exhibits superior performance than the other two plans in terms of quickly dissipating the queue and improving the overall intersection efficiency and potential safety performance. There are, however, still some limitations of this study, such as only a single intersection was studied and the arrival flow rate remained constant for the entire simulation. In future studies, more realistic traffic with various arrival flow rates and multiple intersections on a corridor may be studied to provide more insightful findings.

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