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Research Article

Effects of Implementing Night Operation Signal Coordination on Arterials

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Traffic signal coordination, which connects a series of signals along an arterial by various coordination methodologies, has been proven as one of the most cost-effective means for alleviating traffic congestion. Various metropolitan planning organizations (MPO) or transportation management centers (TMC) have included signal timing updates in their strategic plans. However, in practice, signal coordination is usually implemented when traffic volume is heavy (i.e., during peak hours). For the rest of the day, the free operation strategy is usually used to reduce the waiting time of uncoordinated phases. However, this free operation strategy may result in the loss of operational efficiency on the major street. Currently, implementing signal coordination during off-peak hours is rare in the U.S. since there is lack of an efficient method that considers traffic operations for both the major and the minor streets. Therefore, this research provides a novel method that balances the control delays between the major street and the minor street. The procedure is to optimize the splits of the major street while also using the reservice strategy in the signal controller for the minor street. Microsimulation modeling was employed to assess the performance of traffic signal coordination during off-peak periods. Results show that, under reasonable splits, the coordination effect on the major street can be achieved and protected with an acceptable delay to minor street traffic. The strategy can be immediately implemented to reduce travel time for major street traffic.

1. Introduction

Over the years, signal coordination has been adopted as an effective measure for alleviating congestion, and thus signal coordination plans are typically implemented during peak hours. In current practice, when traffic volume is low, signal coordination is usually deactivated from the controller. Instead, a free operation strategy, a fully actuated coordination that requires detecting all movements, is typically employed. This is mainly because signal coordination often requires more green time assigned to the central street to achieve a guaranteed mainline capacity. However, when mainline traffic flow is not heavy, the extra time for mainline cannot be used by the side street, resulting in the loss of intersection capacity. Hence, it has been a common sense that signal coordination may not be necessary when traffic volume is relatively low, such as at night. Nevertheless, although free operation can balance the waiting time of each approach, it may break the mainline traffic flow at any time once vehicles are on the side street, which may make drivers experience frequent stops and produce more emissions.

There has been a sustained debate about the suitable signal control strategy that should be used during nighttime. The key point is to balance the tradeoffs between the delays in the coordinated and non-coordinated phases. Currently, the free operation strategy has been commonly adopted in practice. However, even though most agencies prefer to use the free operation under low volume conditions, no evidence indicates that running the free operation is a better solution compared to coordinated plans from the perspective of operational efficiency. Moreover, the use of signal reservice strategy enables flexible switches between side street (non-coordinated) and main street (coordinated) phases, which avoids the conflict between the main street coordination delay to the side street. With this consideration, this research investigated the operation difference by comparing the simulated performance of two signal operation strategies under a series of low volume conditions in VISSIM.

The remainder of this paper is divided into the following parts: first, a comprehensive literature review regarding the prevalent signal timing strategies was conducted. Then, a feasible methodology that can balance the mainline progression effects and the minor street waiting time under a low volume condition was proposed. After that, the effects of the proposed strategy by comparing it with the free operation using field data and microsimulation modeling were evaluated, and finally, conclusions and recommendations were summarized.

2. Literature Review

The concept and strategy of signal coordination have been proposed and developed in the last century; currently, it is one of the critical methods in protecting cities from congestion. Bandwidth progression [1] was developed and gradually became a major optimization method. Furthermore, two algorithms based on bandwidth optimization were sequentially proposed: half-integer algorithm [2] and the mixed-integer linear programming [3], which can be used to derive maximum bandwidth. While simply achieving the maximum bandwidth is not enough, the interference elimination function [4] was later developed, and then phase sequences and offsets were also becoming adjustable. These parameters can effectively influence the signal coordination effect.

Based on these parameters, some algorithms and useful strategies were carried out to benefit the signal coordination. A software PASSER-2 [5] was developed, which enabled flexible phase adjustment. Little et al. [6] proposed the MAXBAND algorithm which involved offsets, sequences, speeds, and a series of parameters. Gartner [7] further refined MAXBAND to a multiband model, which can accommodate variable bandwidths. Abbas [8] et al. developed a real-time offset transition algorithm, which has the potential to cater to the traffic flow. Tian investigated a series of signal coordination strategies for practical use, including the system partition technique [9], the split-phasing operation [10], and the lead-lag phasing operation [11]. After that, studies focusing on improving intersection [12] and interchange control [13, 14] were continuously studied by different researchers.

As for low volume conditions' signal coordination, to the best knowledge of the research team, little is mentioned in the existing federal or regional signal timing manual since the coordination is originally for conditions where significant volumes appear. Although several researchers mentioned how to determine time-of-day (TOD) [15–17] breakpoints, what plan should be used after peak hour remains a problem. There are several alternative operational strategies for low volume conditions.

In the MnDOT Traffic Signal Timing and Coordination Manual [18], traffic actuated control was recommended as the countermeasure for low volume conditions, in other words, the coordination plan was not recommended. Abdelghany et al. [19] also mentioned that the fully actuated operation is preferred under low volume conditions; however, they also have concerns that not every intersection is capable of fully actuated operation due to intersections lacking detectors.

Another practice is to mimic stop/yield operation when the volume is low by using the flashing mode in the signal controller. Bonneson et al. [20] mentioned that, during low volume periods, the flash operation can be used. However, safety issues were raised by others since data show that this strategy increased the right-angle crash rate. Therefore, the pretimed signal with a plan suitable for the low volume condition is also recommended. Messer et al. [21] mentioned that, at low volumes, any reasonable signal timing strategy works well as long as the detectors work and traffic signals are coordinated.

However, the aforementioned research did not state what strategy should be used under different low-volume conditions. Later, Andalibian [22] mentioned that if the percentage of stops along a non-coordinated arterial exceeds 50, then coordination is recommended. When the percentage of stops is 20 or lower, the actuated operation is recommended. He also raised another criterion [23] based on volumes; signals should be coordinated when traffic volumes in the peak direction for major street reaches 750 vph for arterials with two lanes in each direction and 850 vph for three lanes in each direction. Another practice from the Washington Department of Transportation [24] stated that 400 vph should be the threshold for whether to use signal coordination or not. However, these studies still did not provide solid evidence that their threshold can balance the operational efficiency and minor street waiting time. The engineers of the City of Laguna Niguel [25] mentioned that, during nonpeak times, drivers are less willing to accept the minor street and left turn delays that are part of coordination during quieter/lower volume times of the day. Therefore, a novel strategy that can better balance coordination effects and the minor street delay is necessary. Besides, recent research indicates users following traffic rules will have a lower crash rate under coordination, and safety concerns regarding coordination were also examined and cleared [26] for using signal coordination.

3. Methodology

Although operational efficiency derived from the bandwidth optimization is an important consideration in the determination of whether or not to use a coordination plan, it is

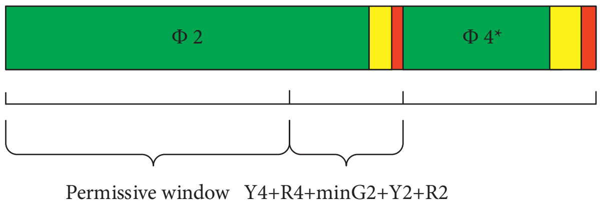

Figure 1: Permissive window of two phase control. Y4: yellow time of phase 4; R4: all red time of phase 4; minG2: the minimum green of phase 2; Y2: yellow time of phase 2; R2: all red time of phase 2.

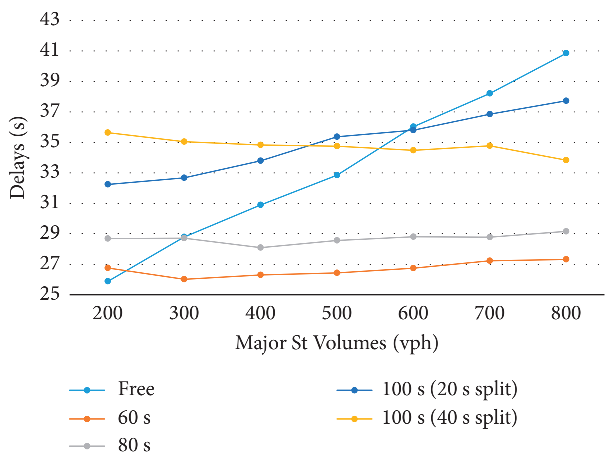

Figure 2: Average delay under minor street volume of 50 vph.

unable to directly reflect minor street drivers' expectations since minor street drivers may still experience long waiting times even if the overall intersection operational efficiency is good. However, in practice, driver expectation also plays an important role in operational performance assessment, such as minor street drivers may get frustrated if the coordination phases do not gap out especially when no vehicles on the major street. Therefore, to satisfy drivers' expectations, this research proposes an analytical model to calculate the probability of stopping using basic signal timing parameters. According to field observations and through expert interviews, a 20-second waiting time (control delay) was selected as the maximum acceptable tolerance time for drivers if no conflict vehicles were present.

At a signalized intersection, the probability of a car stopping more than 20 s at the intersection can be calculated according to the geometric distribution, as follows.

$$p = \max\left(0, 1 - \frac{C - G_e + 4 + 20}{C}\right), \quad (1)$$

where p is the probability of a car experiencing a stop of more than 20 s; G_e is the effective green time of the major street; and C is the cycle length. The reason for adding 4 seconds is because most drivers tend to choose to release the accelerator or use a light break once they see the red light.

With the above model, it is capable to estimate the probability of waiting for more than 20 s under different conditions, which is critical for determining the acceptable signal timing parameters.

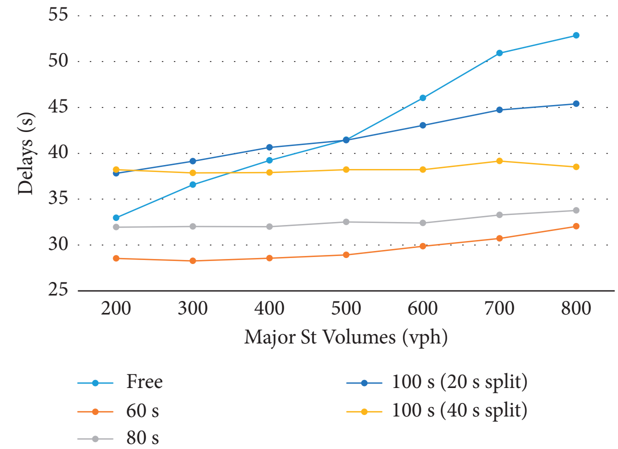

Figure 3: Average delay under minor street volume of 100 vph.

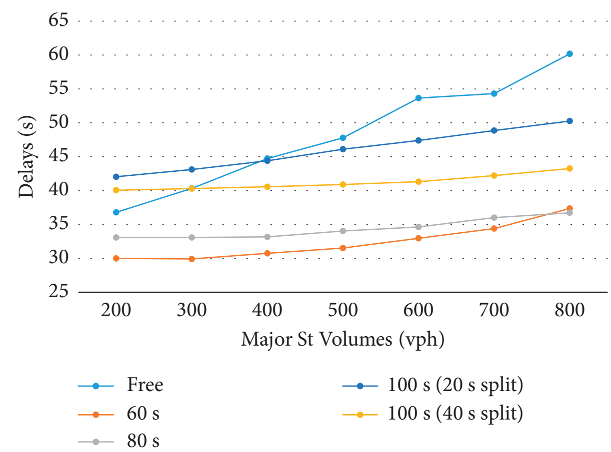

Figure 4: Average delay under minor street volume of 150 vph.

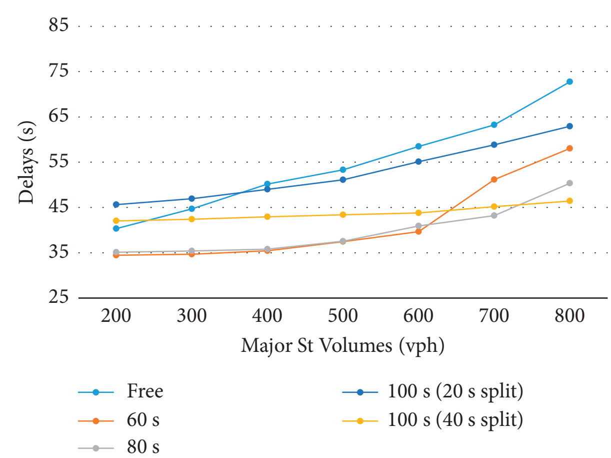

Figure 5: Average delay under minor street volume of 200 vph.

Recently, with the evolution of signal controllers, some new features and technologies have been applied to aid in the operation of intersections. To better satisfy drivers' expectations (i.e., minimum waiting time), a reservice strategy can be applied as it is capable of better assigning the capacity to

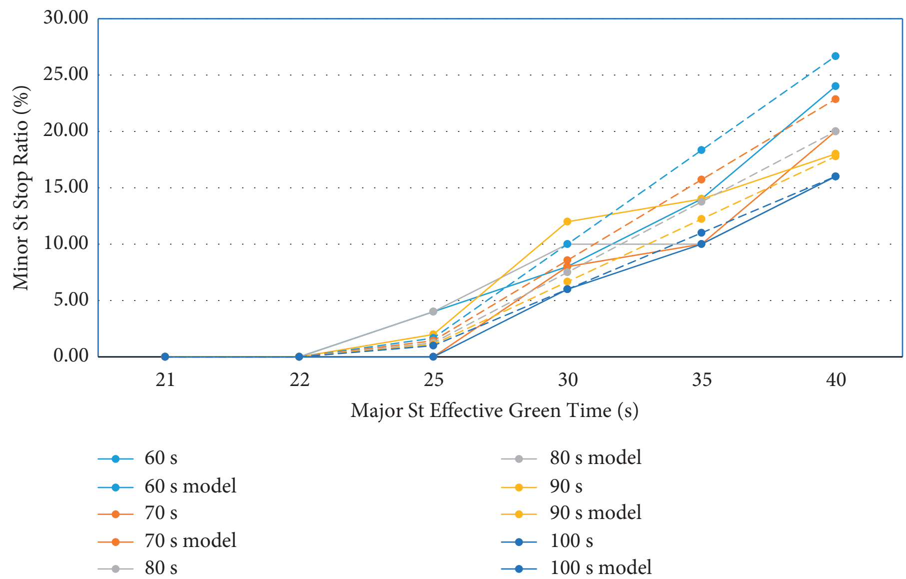

Figure 6: Minor St tolerance stop ratio of coordination plans under the volume of 50 vph.

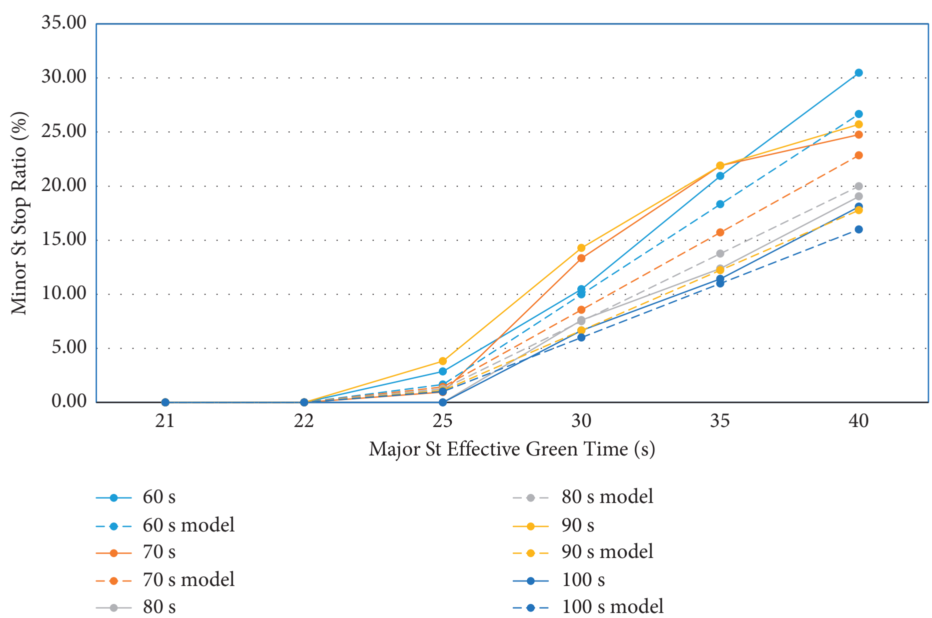

Figure 7: Minor St tolerance stop ratio of coordination plans under the volume of 100 vph.

different movements and improving the operational efficiency. The concept of this strategy is when the major street traffic flow is not platooned, the coordinated phase can be terminated and temporarily transfer right-of-way to non-coordinated phases. After serving the non-coordinated phase, if the coordinated phase is still in the permissive window and has vehicles to be served, the remaining green time will be returned . Therefore, the reservice strategy is considered to benefit operational efficiency. The feature was intentionally designed to reduce the delay in the movements with nonplatoon vehicles. However, insufficient attention was given to its potential for coordination during nonpeak periods. With the reservice strategy, coordination during nonpeak periods becomes feasible. The reservice strategy can happen to some of the in-use phases in their permissive windows. The details of the reservice logic may vary by case, and an example of the permissive window of a two-phase signal control strategy is shown in Figure 1.

The coordinated phase is phase 4. From the figure, phase 2 occupied most of the cycle time. During the permissive window, if phase 2 has no vehicles to serve and phase 4 has vehicles, phase 2 can gap out and switch to phase 4. After serving phase 4, if phase 2 has vehicles waiting and the current time is still within the permissive window, the green signal can be switched back to phase 2 until all phase 2 vehicles are served or until the end of the phase.

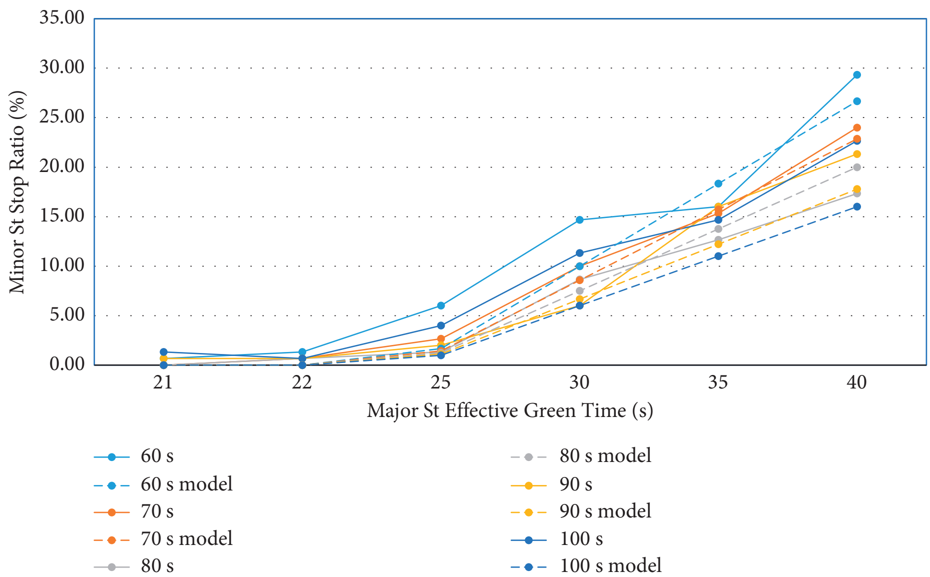

FIGURE 8: Minor St tolerance stop ratio of coordination plans under volume of 150 vph.

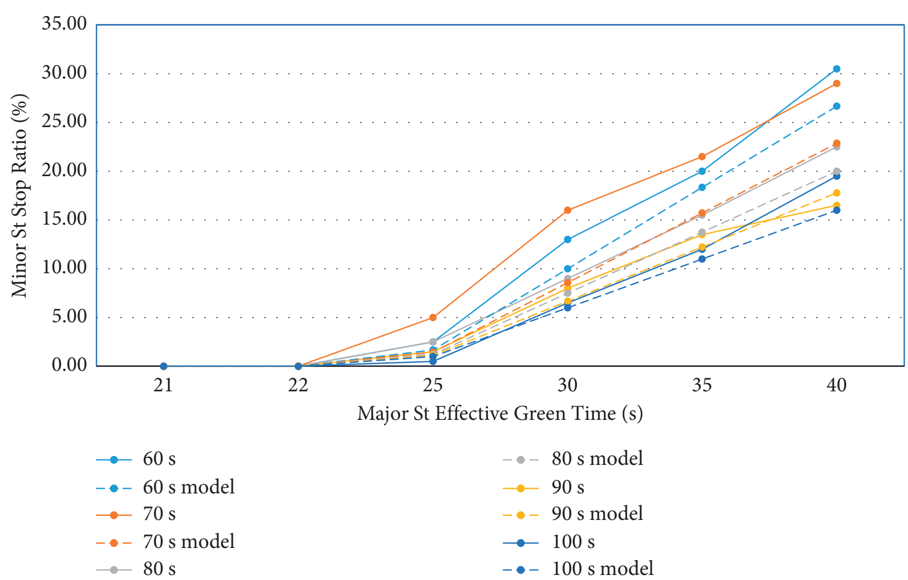

FIGURE 9: Minor St tolerance stop ratio of coordination plans under volume of 200 vph.

4. Operational Efficiency Assessment

To make sure the strategy is effective, it is necessary to compare the operational efficiency between the free operation strategy and the coordination strategy. The simulation modeling was conducted in the PTV VISSIM. The reservice option was selected before simulation, and all the phases were placed with no recalls. The purpose was to ensure the reservice function was applied. The North McCarran Blvd in Reno, Nevada, was selected as the simulation testbed. Coordination plans under three-cycle lengths (i.e., 60 s, 80 s, and 100 s) and free operations were tested under various major street traffic volumes (i.e., 200 vph–800 vph with an iteration interval of 100vph) and minor street traffic volumes (i.e., 50 vph–200vph with an iteration interval of 50vph). The 100 s cycle length has two conditions: major street split of 20 s and 40 s. Simulated delays are summarized in Figures 2, 3, 4, and 5.

Results show that, under low minor street volume conditions, the average delay under free operation is the lowest when major streets are also under low volume conditions. However, the delay of free operation increases sharply as major street volume increases, which suggests the performance of the free operation is unstable. On the other hand, the delay under the 60 s cycle plan is almost the same as the free operation when the major street volume is 200vph, as shown in Figure 2. While for the rest cases, it significantly outperforms free operation. From Figures 2 to 5, although the minor street volume increases, the 60 s cycle plan always has the lowest delay in most of the cases, with the

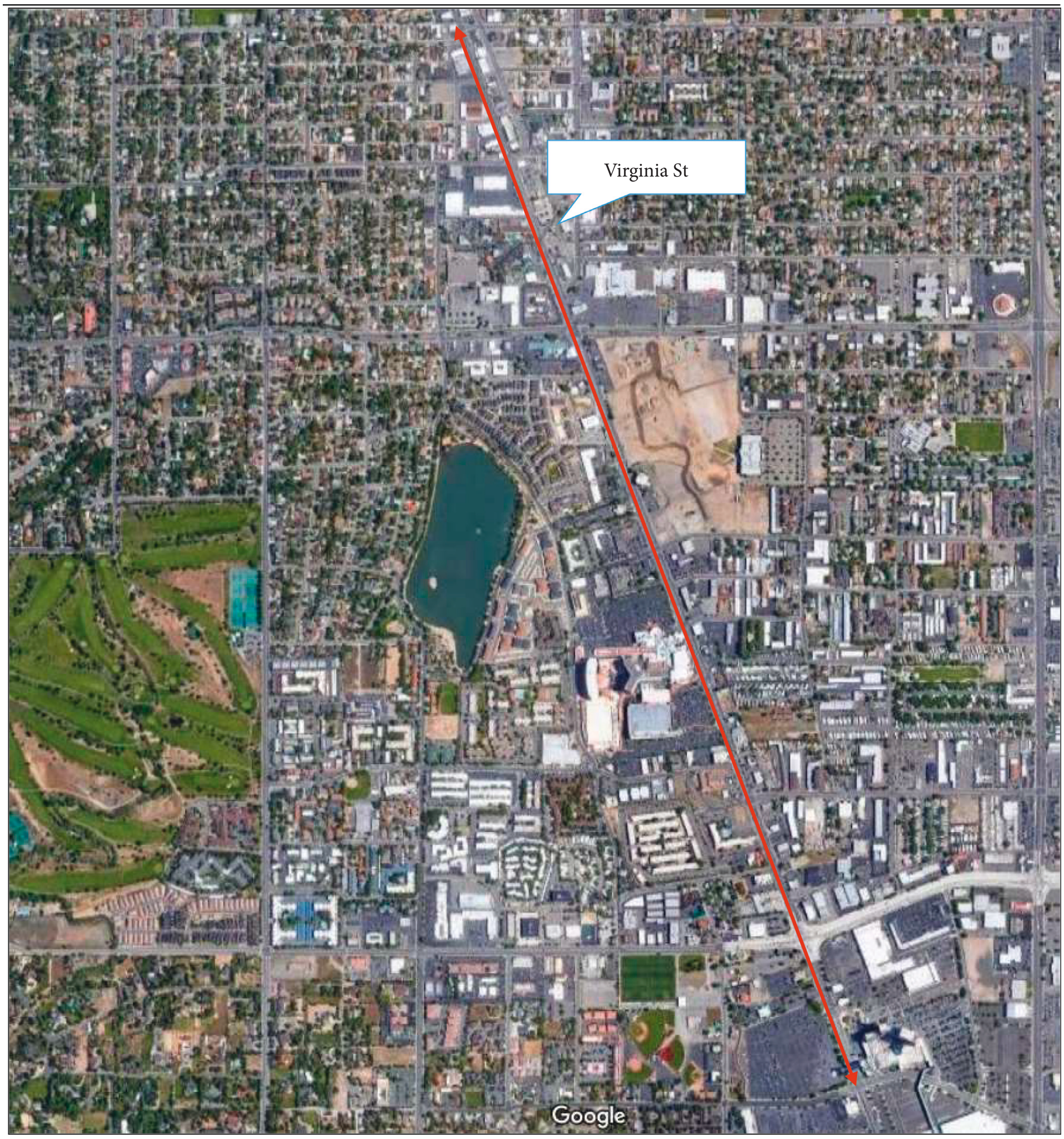

Figure 10: The scope of coordinated segment of Virginia St.

80 s cycle plan being the second optimal plan. Therefore, it can be concluded that, with an appropriate cycle length, the overall intersection efficiency under coordination is better than free operation for low volume conditions.

5. Stop Rate

In addition to delay, stop rate and stop time are also crucial, especially for the side street vehicles. To simulate vehicle stopping conditions under different volume scenarios, a single-lane minor street was constructed in VISSIM which crosses another single-lane major street. Since a vehicle is assumed to arrive randomly following the uniform distribution during a period (within a cycle or during the whole analysis period), the probability that a vehicle arrives at each timestamp is equal. Therefore, the probability that a vehicle makes or does not make at least a stop that is longer than 20 s can be calculated via equation (1).

To validate whether the calculated stop ratio matches the actual stop ratio, the simulation process was conducted under four volume levels and five cycle lengths. Stop ratios are collected and illustrated in Figures 6, 7, 8, and 9. The solid lines indicate simulation results, and dash lines indicate calculation results from the model.

Results show that stop ratios under different volume levels have a similar increasing trend. In general, the simulated stop ratios are highly consistent with the model estimations. From all figures, it can be found that the minor street stop ratio can maintain a relatively low level (about 20%) when the major street split is less than or equal to 35 s. For minor street efficiency, according to calculated probability and stop ratio simulations, a larger cycle length will

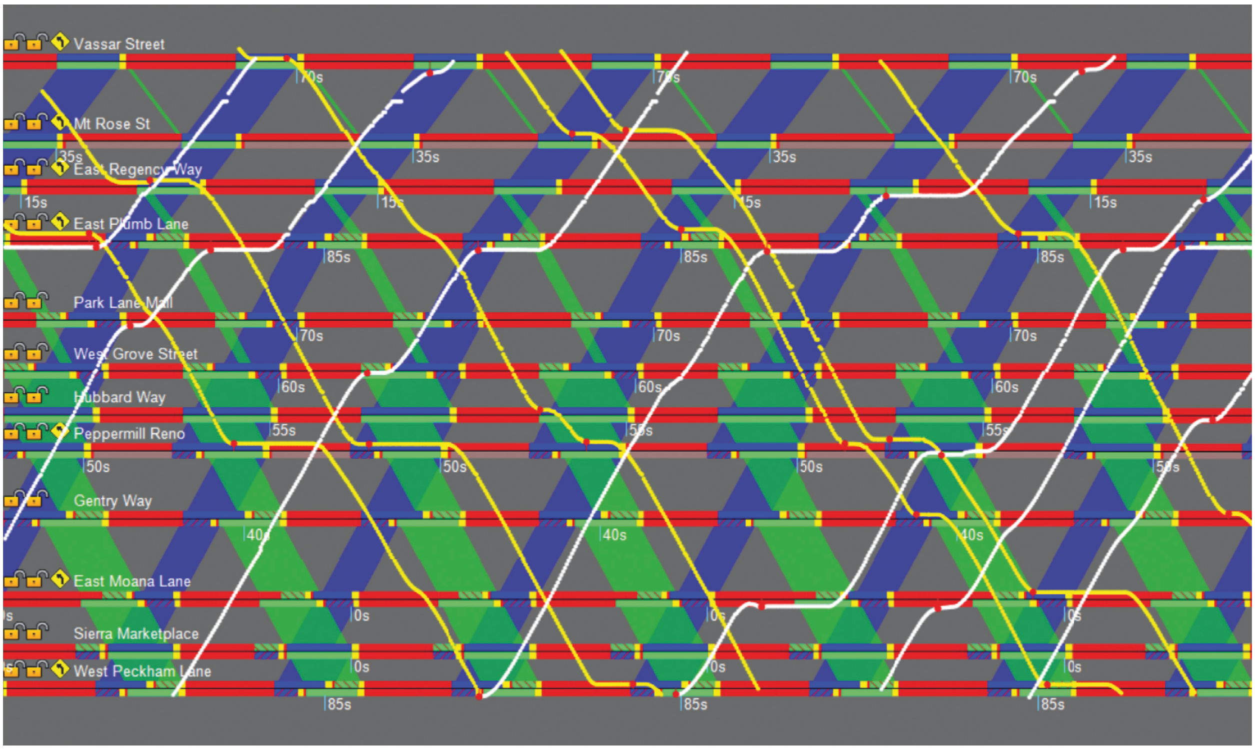

Figure 11: Vehicle trajectories under free operation.

better benefit the minor street. However, according to the North McCarran Blvd practice, with a shorter cycle length, the overall intersection performance becomes better, as indicated in Figures 2 to 5. The reason is that a shorter cycle length could benefit the design of the coordination bandwidth. On the other hand, the reservice strategy has already reduced minor street delays regardless of the cycle length that was used. Based on all the above, using a shorter cycle length is a compromise that displays benefits from each method.

6. Field Validation

To provide a conclusive recommendation, field implementation and validation are necessary. A signal coordination plan for the night condition was developed and implemented along Virginia Street in Reno, Nevada. Twelve intersections were selected between Peckham Lane and Vassar Street, as shown in Figure 10. This segment was chosen due to the relatively significant side street volumes reported that access Midtown and Downtown via this route. Since the number of signals in coordination is more than 10 and the pedestrian movements are relatively heavy, the splits of coordinated phases for these intersections range from 27 s to 56 s; therefore, some of the splits are larger than 35 s. The planned operation time is from 8:00 pm to 10:00 pm. Vehicle trajectory data were collected through TranSync-M software during the operation time. The trajectories of the probe vehicle on the major street under free operation and coordinated operation were extracted, as shown in Figures 11 and 12, respectively. The background time-space diagram (TSD) reflects the proposed signal timing plan, the TSD of the free operation varies by time, in Figure 11, and while the free operation background is kept the same as the proposed plan for the convenience of comparison between their trajectories.

From the figures, most of the trips experienced two or three stops during the data collection period, indicating that, on average, the probe vehicle only stops one time out of five intersections. This suggests the performance of both the free operation and coordination has good results. While it is hard to capture the differences simply from visual observation, to validate the difference, the trajectories information was analyzed by the incorporated performance evaluation algorithm: signal performance index [27]. Table 1 shows the detailed performance parameters under free operation and coordination strategies. Results show that the overall speed increased by approximately 3 mph after the coordination; the improvements are significant in both the southbound and northbound directions. For the number of tops, it is also reduced according to the stop score. The quality of signal timing generally indicates the two directions was also upgraded from B+ to A and from B to A−. Therefore, the coordination plan provided better performance than free operation on the mainline.

Both trajectories and videos of vehicles passing minor streets were collected for evaluating the side street performance. Based on the 100 samples collected from the field, this research found that vehicle waiting times vary from 0 s to 72 s. However, most of the waiting experiences did not make the minor street drivers become impatient since there were vehicles on the major street. Therefore, the maximum times

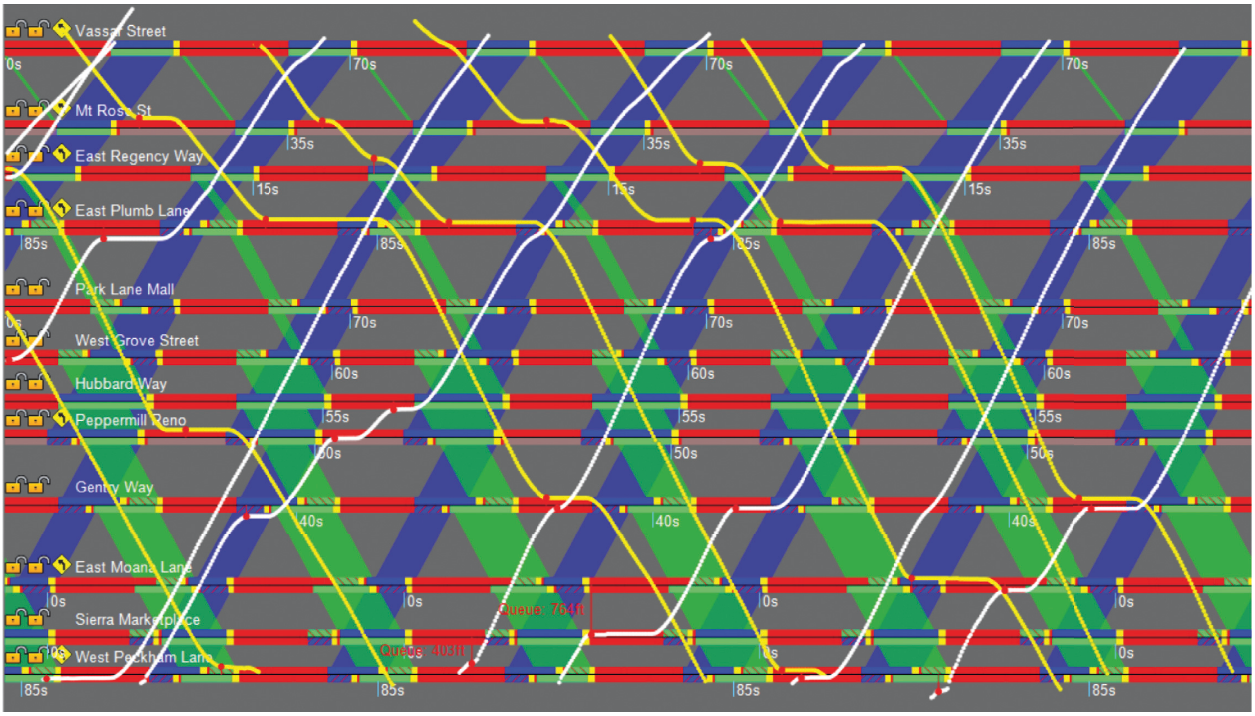

Figure 12: Vehicle trajectories under signal coordination.

Table 1: Performance results under free operation and signal coordination.

Signal strategy	Free operation strategy					Signal coordination strategy				
Performance measure	Avg. speed (mph)	Avg. travel time (s)	Avg. delay (s)	Stop time (s)	Signal quality	Avg. speed (mph)	Avg. travel time (s)	Avg. delay (s)	Stop time (s)	Signal quality
Evening plan avg.	20.6	320	110	82	B	23.4	282	72	53	A
Evening plan NB	20.2	327	116	78	B+	25.1	263	54	35	A
Evening plan SB	21.1	313	103	87	B	21.8	303	92	73	A-

without major street vehicle appearances were collected, and they varied from 0 to 35 s. However, only three samples exceed 20 s, among which two of them had pedestrian calls. Therefore, the minor street driver is less likely to become impatient when the night plan is incorporated if appropriate signal coordination and reservice are incorporated.

7. Concluding Remarks

A critical concern in the implementation of a coordination plan during nonpeak hours is that minor street vehicles may unnecessarily wait for the major street operation to terminate particularly when there are no vehicles on the central street. This research provided a feasible approach to keep the progression on the major street without having the minor street vehicles waiting for a long time. The method is to set the major street splits as small as possible so that minor street vehicles can have a larger possibility to proceed the intersection with an acceptable stop time. The reservice strategy was applied to eliminate the situation where minor street vehicles cannot pass once the early return happens (i.e., the green signal will always hold to the end of coordinated phases). A 20 second threshold was used as the acceptable waiting time, which has been recommended by several professional engineers from the Regional Transportation Commission of Northern Nevada. Engineers may also adopt other values as the threshold according to different regions and driver behaviors and use the proposed model to calculate the appropriate splits corresponding with the desired stop probability. Although pedestrian movement may also contribute to a longer wait time, the delay caused by pedestrians can be tolerated by drivers since this is usually considered as expected delay. In terms of the influence of pedestrian crossing on mainline traffic, it can also be reduced by turning on the stop-in-walk feature in the signal controller. Therefore, in general, the proposed approach solves the problem of unnecessarily minor street vehicles waiting with the preservation of the major street coordination. However, there remain several issues not solved in this research such as the extra waiting time caused by the queue or the pedestrian crossing impact on the coordination. In the current model, extra waiting time was not considered since the low volume condition is expected to have little probability of encountering the queueing issue; future research may further explore the effects of the pedestrian crossing on major street traffic operations, and the field performance comparison between the traditional coordination plan and the proposed coordination plan could be conducted.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare there are no conflicts of interest in this research.

Authors' Contributions

RY and ZT contributed to study conception and design; RY, YZ, and GY were responsible for experiment design and data collection; RY and YZ took part in experiment design and data collection; RY, GY, and YY prepared the draft article. All authors reviewed the results and approved the final version of the manuscript.

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