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# Urban Intersection Modelling for Signal Coordination and Adaptive Traffic Control under Heterogeneous Traffic Condition: A Case study of Keshar Mahal and Durbar Marg Intersections

Nhuja Bajracharya[a*], Subhash Dhungel[b]

[a]Nepal Engineering College – Center for Postgraduate Studies (nec-CPS), Pokhara University, Lalitpur, Nepal
[b]Traffic and Transport Unlimited Solutions,Chakupat, Lalitpur,Nepal

**Abstract**

This study aimed to improve the operational performance of two closely-located intersections, Keshar Mahal and Durbar Marg, in Kathmandu, Nepal. The current traffic management system was causing long queue lengths, spillback and cumulative delays at both intersections. Using advanced lane-based micro-analytical tools such as SIDRA INTERSECTION, simulations were conducted to evaluate different phase configurations and signal timing strategies under isolated and coordinated conditions for both pretimed and actuated signalization. The results revealed that pretimed signal coordination with an optimal network signal cycle was the most effective option. This strategy resulted in a 33.4% reduction in total travel time, a 48.8% decrease in total control delay, and an average control delay reduction of 49.2%. Additionally, it led to significant improvements in intersection performance, including a 62.1% decrease in the 95th percentile back of queue at the Keshar Mahal intersection and a 13.9% decrease at the Durbar Marg intersection. The study also compared the results to the existing network in terms of individual intersection performance and network-wide performance, showing the potential benefits of the proposed strategy in improving traffic flow and reducing delays at the intersections.

*Keywords*: Pretimed Signalization; Actuated Signalization; Signal Coordination; Spillback; Intermittent Stop; Travel Time; Queue Length.

## 1. Introduction

Traffic congestion is a common problem in many cities, including Kathmandu, Nepal. As the economy grows, the number of vehicles on the road increases, leading to a demand for wider roads. However, limited space and population growth make it difficult to widen roads, thus the need for more efficient traffic management systems. However, these systems developed in developed countries cannot be implemented directly in Nepal as traffic conditions are different. To improve traffic flow and reduce delays, travel time, and queue length in urban areas without building new infrastructure, optimizing traffic signal timing is important. In Kathmandu, most of the intersections are at-grade and traffic signals are installed in some of them but are not updated to current traffic conditions. During peak hours, traffic police manually control the signalized intersections as the existing timing is inefficient. This leads to intersection performance being dependent on the judgment and perspective of the traffic police without scientific analysis. This can result in long queues and delays when the intersection is controlled by an inexperienced traffic police. Two intersections, Keshar Mahal and Durbar Marg, cause significant traffic congestion, particularly during peak hours. The current traffic management system is unable to clear the intersections quickly, resulting in long queues that spill over into other intersections. Improving the traffic control system at these intersections is necessary to improve traffic flow and reduce travel times.

This study aims to enhance traffic control systems at the Keshar Mahal and Durbar Marg intersections in Kathmandu by using advanced lane-based micro-analytical tools. The goal is to evaluate the current performance of the intersections, compare the performance of pretimed and actuated signal timing under isolated and

* Corresponding Author. Tel.: +977-9843104208
*E-mail address:* nhujabajracharya@gmail.com

coordinated signalization, and suggest the best signalization scenario. The study aims to improve traffic flow by reducing stops and delays, allowing large groups of vehicles to move smoothly, and preventing congestion from spilling over from one intersection to another. In addition, it aims to improve pedestrian mobility and safety, decrease vehicle emissions, reduce accidents, and improve emergency response times in the study area, and delay the need for street widening.

Traffic signal retiming improves traffic flow and reduces congestion by adjusting the timing of traffic signals, resulting in shorter commutes, better air quality, fewer accidents, and less driver frustration (FHA, 2007). Inefficient traffic signals can cause delays, disobedience, increased use of less adequate routes and more rear-end collisions, which affects all road users. Improper or unjustified traffic signals are the root cause of these issues (FHA, 2009). Properly designed and timed traffic signals can improve the flow of people and vehicles, increase road capacity, decrease accidents, and enhance accessibility for pedestrians and side street traffic (Koonce & Rodegerdts, 2008). Retiming traffic signals is a cost-effective way to improve traffic flow along highways, with a typical benefit to cost ratio of 40:1 (Sunkari, 2004). Signal retiming at New Baneshwor intersection in Kathmandu resulted in a significant reduction in travel time and delay (Shrestha & Marsani, 2017).

Improvement of traffic signal timing and using traffic signal coordination are two of the most important strategies for reducing delay, travel time and queue length in urban area (Nesheli, Puan, & Roshandeh, 2009). Traffic signal coordination synchronizes multiple intersections to improve the flow of traffic. Factors such as proximity of intersections and traffic volume on coordinated streets are considered when deciding to implement coordination. Coordination is most effective when intersections are close and there is heavy traffic on the coordinated street. Typically, intersections within 800 meters of each other along a corridor should be coordinated, unless they operate on different cycle lengths (FHA, 2007). Traffic signal coordination establishes relationships between adjacent traffic signals using offsets (time difference in the start of the green phase between adjacent traffic control signals, in seconds) (MDOT, 2013). Coordinated signal systems self-regulate speed, where those driving too fast will arrive at a red signal and have to stop, and those driving too slow will miss the green signal and not be able to proceed (Garber & Hoel, 1999). The "ideal offset" is the time gap between the start of the green phase of the signal at a downstream intersection and the arrival of the first vehicle in a platoon at that signal, assuming the platoon is moving through an upstream intersection (Roess, Prassas, & McShane, 2007). Coordinating signals with optimized offset values results in significant reduction in delay and travel time values (Bhattarai & Marsani, 2015).

Adaptive traffic control systems (ATCS) belong to the latest generation of signalized intersection control. It adjusts traffic signal timings in real-time based on current traffic conditions, demand and system capacity using algorithms that optimize signal's split, offset, phase length and phase sequences to minimize delays and reduce stops. It requires extensive surveillance and communication infrastructure with central and/or local controllers (Stevanovic, 2010). Adaptive traffic control systems adjust signal timings in response to changes in traffic flow to overcome the limitations of pre-timed control and adapt to fluctuations in traffic demand (Ravikumar, 2012).

## 2. Methodology

### 2.1. Study Area

The Keshar Mahal and Durbar Marg Intersections are two major intersections located in Kathmandu, Nepal. They are situated near significant landmarks such as the Royal Palace Museum, Indian Embassy, British Council, Thamel, and the historic Rani Pokhari. The intersections are located at coordinates 27.713601°N, 85.315389°E and 27.713127°N, 85.317840°E respectively. The Keshar Mahal Intersection has four approach legs - Jamal leg (520m south), Thamel leg (300m west), Lainchaur leg (350m north) and Durbar Marg leg (225m east). The Durbar Marg Intersection has three approach legs- Durbar Marg leg (335m south), Keshar Mahal leg (225m west) and Nag Pokhari leg (405m east).


Figure 1: Location Map of Study Area

## 2.2. Data Collection

The data collection methodology for this study included the use of multiple tools to gather both primary and secondary data. A drone survey was conducted with the aid of ground control points and DGPS in order to collect geometric details of intersections. Video cameras were also used to record traffic flow at intersections, and the recorded footage was used to count the classified traffic and pedestrian volume, as well as the phase timing. Drone video and imagery were also used to deduce data about vehicle movement, including measurements of queue space and vehicle length. In addition to these methods, data on traffic flow, speed, and capacity was also collected. Overall, this study employed a range of data collection tools in order to gather detailed and accurate information about the intersections being studied. The study also used secondary data, including the PCU factors adopted by the Kathmandu Valley Intelligent Traffic System Project (DOR, 2022) and Basic Saturation flow as suggested by Indian Highway Capacity Manual (Council of Scientific and Industrial Research, 2017). The specialized data collection methodology used in the study is further discussed;

### 2.2.1. Intersection Geometry

An unmanned aerial vehicle (UAV) survey, also known as a drone survey, was conducted to gather geometric details of intersections. This survey method involved the use of ground control points established with differential global positioning system (DGPS) technology, as well as the use of a drone to capture overlapping images of the survey area. The survey team used the “SW Drone” software to create a flight plan and mobilized to the field to fly the drone, a DJI MAVIC PRO, according to the predetermined flight plan. The drone imagery was then processed using photogrammetry software (Agisoft) and ortho-rectified using the DGPS-established ground control points. The resulting ortho-rectified, geo-referenced imagery had a resolution of 5cm per pixel and was used to extract the required geometric details.

### 2.2.2. Vehicle Calibration and Movement Data

Data relevant to vehicle movement at an intersection was gathered using a drone equipped with a video camera. The drone, a DJI MINI 3 Pro, hovered over the intersection for 40 minutes and captured video footage of the vehicles. From this footage, a number of measurements were made in AutoCAD, including queue space and vehicle length for different vehicle types.

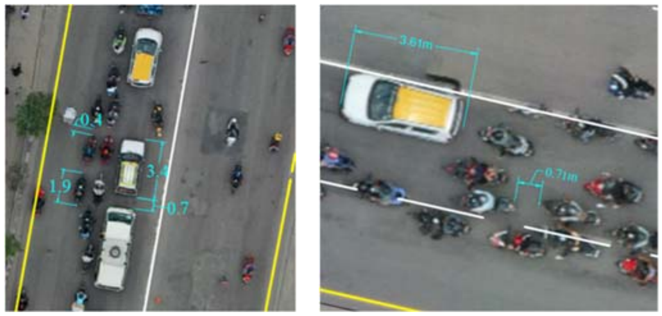



Figure 2: Sample for measurement of Queue Space and Vehicle Length

The drone video was also used to identify typical negotiation paths of vehicles and to measure the negotiation distance, radius, and downstream distance for each origin-destination (O-D) movement. The data collected from the drone video and imagery was ortho-rectified to an actual scale and used to deduce information about vehicle movement at the intersection.


Figure 3: Sample of Negotiation Distance and Radius Measurement

### 2.2.3. Speed

The study used the manual short-base method to conduct speed survey and gather data on vehicle speeds. This method involved marking a 30-meter short base on the road with red spray paint, where vehicles passing over it were timed. A minimum of 75 observations were taken for each approach to estimate the speed, with all observations made during off-peak hours (12:00 PM to 3:00 PM) (TRB, 1993).

In addition to the cruise speed survey, a number of observations (more than 10 in each direction) of negotiation speed for different types of vehicles were made by timing the vehicles as they traveled the measured distance (negotiation distance for through-moving vehicles and negotiation radius for turning vehicles) from the approach stop line to the exit side stop line, along the typical vehicle path for each movement, using the recorded drone video. A number of observations (more than 10 in each direction) of saturation speed for different types of vehicles were also made by timing the vehicles as they traveled the baseline distance (30 meters) near the stop line for each movement, using the recorded drone video (V., Pandey, Rao, & B.K., 2016).

### 2.2.4. Back of Queue

To measure the distance from the back of a queue to the stop line at an intersection, seven people were deployed to the approaches of the intersection during the morning peak hour for three days. Using the “SW Maps” application on their mobile phones, they recorded the coordinates of the back of the queue in the field. These coordinates were then plotted in GIS software to measure the distance from the stop line.

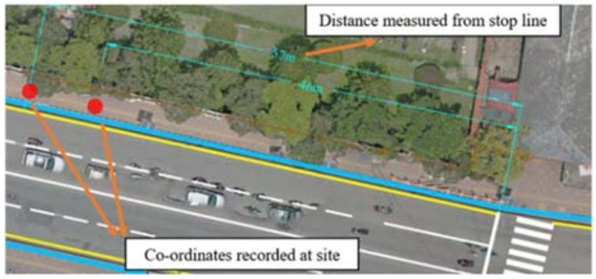



Figure 4: Sample of Back of Queue measurement

### 2.3. Data Analysis

The data collected for this study was analyzed using the SIDRA intersection model. SIDRA intersection is a software is used for designing and evaluating various types of traffic control systems, including signalized intersections, pedestrian crossings, roundabouts, single point interchanges, roundabout metering, two-way stop sign control, all-way stop sign control, and give-way/yield sign control (Akcelik & Besley, 2003). SIDRA Intersection is a traffic evaluation tool that provides estimates of capacity and performance statistics such as delay, queue length, and stop rate, using lane-by-lane and vehicle drive-cycle models, and an iterative approximation method. It is calibrated using the Highway Capacity Manual (HCM) version of SIDRA Intersection (TRB, 2000). Performance Index (PI) is a measure that combines several other performance statistics, and therefore can be used as a basis for choosing between various design options (the best design is the one which gives the smallest value of PI) (Akcelik and Associates, 2018).

$$PI = Tu + w1.D + w2.K.H/3600 + w3.N' \quad (1)$$

Where,

*Tu* : total uninterrupted travel time (veh-h/h),
*D* : total delay due to traffic interruption (veh-h/h)
*H* : total number of effective stops (veh/h)
*K* : stop penalty
*N'* : sum of the queue values (in vehicles) for all lanes, and
*w1, w2, w3* : delay weight, stop weight, and queue weight values, respectively

The study included calibration and validation of the model using field observations and traffic data. The model was then used to evaluate various operational performance measures for the existing intersection, including capacity, degree of saturation, delay, and level of service. Alternatives for improving the intersection configuration were also proposed and evaluated. The study also included a network analysis of the intersection, linking it with other intersections to evaluate the impact on overall traffic flow in the area. The results of the analysis were used to recommend improvements to the intersection.

#### 2.3.1. Calibration and Validation

To calibrate the model, field observations of traffic volume and existing signal timing from Day 1 and Day 2 were used to compare the model's output queue length with the actual field queue length. The microsimulation analysis required the difference between simulated and field queue length to be within 20% to meet the calibration goal (FDOT, 2021). The calibration parameters were adjusted until the difference between the model output and field observation was less than 20%. The model was also validated, which is an independent check of the calibration, by comparing the model's output queue length with the actual field queue length from Day 3. This was done to ensure that the results produced by the model are representative of the observed situation (DPTI, 2017).

#### 2.3.2. Intersection Analysis

The study evaluated the operational performance of each intersection as an individual site, without considering coordination with neighboring intersections. This evaluation was done using an existing base case scenario under traffic police operation during peak hour. Different alternatives of phase configuration and signal timing were simulated to determine the optimal operation option for each intersection during peak hour. The simulations were run using both pretimed and actuated signal control systems.

Use of HCM version of SIDRA allows calculations for Signal retiming under the methodology as discussed in HCM (Akcelik and Associates, 2018). The current operational design of the intersection only employs pretimed signal timing and traffic control under the supervision of traffic police. This study, however, explores the use of phase actuation as well, which necessitates the identification of specific phase actuation parameters. The parameters recommended by the Highway Capacity Manual (HCM) are used in the phase actuation analysis (TRB, 2000). The existing intersection does not provide any dedicated phase for pedestrians. This study incorporates pedestrian phases and assigns appropriate parameters for them. Since the existing intersection does not consider pedestrians, a calibration for them was not possible, thus, the parameters recommended by the HCM were used in this case (TRB, 2000).

The effective green time for each phase is assigned based on the ratio of the volume of the lane group to the total critical lane volumes of the intersection. The critical lane group volume for a phase is determined by the lane with the highest volume that has the right of way during the phase (TRB, 2000). Actuated signal timing calculations use the same method as for fixed-time signals, but use actuated signal degrees of saturation instead of practical degree of saturation to calculate the required green times, resulting in unequal degrees of saturation for critical movements. Unlike pretimed signals that use equal degree of saturation (EQUISAT) method as default, it doesn't use maximum cycle time constraint and maximum green times determine the largest possible cycle time (Akcelik and Associates, 2018).

#### 2.3.3. Network Analysis

The study linked the intersections together to form a network, then evaluated the operational performance of this network under traffic police operation. Different alternatives of phase configuration and signal timing were simulated to determine the best operation option for the network during peak hour. The optimal simulations from the intersection analysis were then combined to form network options for further analysis. Both pretimed and actuated signal control systems were used in the simulations.

SIDRA uses time-based signal coordination which calculates the signal offset based on the routes assigned for coordination. This form of coordination uses non-interconnected controllers with time-based coordinators which keep time accurately using power company frequency. This allows coordination without the need for physical interconnection as all intersections use the same power source (Roess, Prassas, & McShane, 2007). SIDRA calculates the start time of "movement effective green times" based on the offsets determined by the program, which are used in modeling platoon patterns (Akcelik and Associates, 2018).

## 3. Results & Discussion

### 3.1. Intersection Analysis

#### 3.1.1. Keshar Mahal Intersection

Simulations of different alternatives of phase configuration and cycle timing were performed for the morning peak hour (10:00 – 11:00 AM). Various phase configurations suggested in SIDRA, as well as some additional configurations commonly used in intersections in Kathmandu, were tested in the simulations.

Table 1. Phase Simulations in Keshar Mahal Intersection

| Options | Scenario | Cycle Length |
|---|---|---|
| A | 5 Phase Existing Phasing | 115 |
| B | 5 Existing Phasing with Optimum Cycle Time | 100 |
| C | 4 Phase Split Phasing with Optimum Cycle Time | 100 |
| D | 4 Phase Leading Right Phasing with Optimum Cycle Time | 140 |
| E | 4 Phase Left Controlled Split Phasing with Optimum Cycle Time | 150 |

| | | |
|---|---|---|
| F | 5 Phase Left Controlled Split Phasing with Optimum Cycle Time | 110 |
| G | 6 Phase Left Controlled Split Phasing with Optimum Cycle Time | 140 |
| H | 6 Phase Left Controlled Split Phasing with Optimum Cycle Time and all red phase | 150 |

The results of the simulations indicate that option F would result in the minimum queue length and lowest Performance Index (PI) when used as a Pretimed Signal Control option. Similarly, option F also yielded the best results as an Actuated Signal Control option.

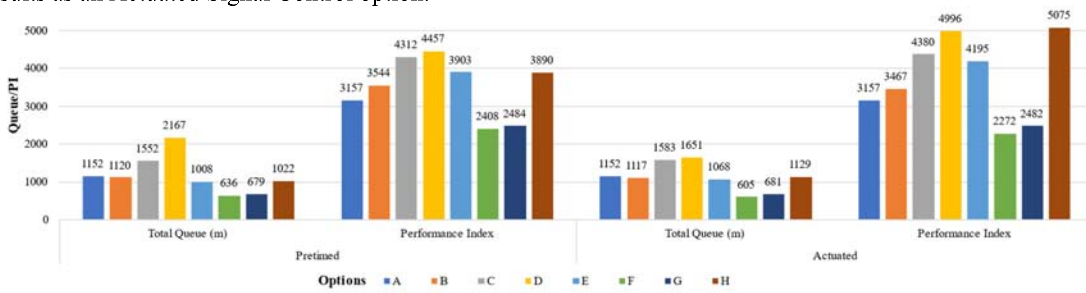



Figure 5: Total 95th percentile queue length and Performance Index in different simulation options in Keshar Mahal Model

The optimal simulation options in both the Pretimed and Actuated analyses (i.e., Option F-Pretimed and Option F-Actuated) were compared to determine the best scenario for the Keshar Mahal intersection when considered as an isolated intersection. The comparison revealed that the intersection would perform better with a lower PI and shorter queue length when operated under Option F of the Actuated analysis. Additionally, the comparison also showed that there would be fewer total effective stops and an improved effective stop rate when the intersection is operated under Actuated Control. Thus, it can be concluded that actuated signal control would be a better option for this isolated intersection.

### 3.1.2. Durbar Marg Intersection

Simulations of different alternatives of phase configuration and cycle timing were conducted during the morning peak hour (10:00 – 11:00 AM) using all the phase configurations suggested in SIDRA and some additional configurations commonly used in three-legged intersections in Kathmandu.

Table 2. Phase Simulations in Durbar Marg Intersection

| Options | Scenario | Cycle Length |
|---|---|---|
| A | 3 Phase Existing Phasing | 116 |
| B | 4 Phase Split Phasing with Optimum Cycle Time | 80 |
| C | 3 Phase Left Controlled Leading Right Phasing with Optimum Cycle Time | 70 |
| D | 3 Phase Left Controlled Modified Leading Right Phasing with Optimum Cycle Time | 90 |

The intersection performance was evaluated in terms of queue length in each leg for various alternatives. The results of the simulations indicate that option C would result in the minimum queue length and lowest Performance Index (PI) when used as a Pretimed Signal Control option. Similarly, option C also yielded the best results as an Actuated Signal Control option. The best simulation options from the Pretimed and Actuated analyses were then compared to select the optimal scenario for the Durbar Marg intersection when considered as an isolated intersection.

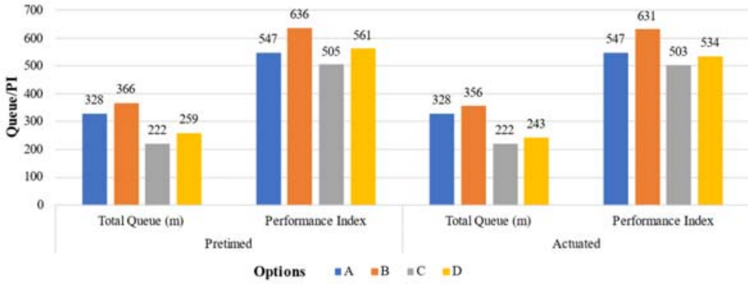



Figure 6: Total 95th percentile queue length and Performance Index in different simulation options in Durbar Marg Model

The comparison revealed that the intersection would have similar queue lengths under both pretimed and actuated control, but the PI would be slightly better in the case of actuated control. Thus, actuated signal control would be a better option for this isolated intersection. Additionally, the comparison also showed that there would be fewer total effective stops and an improved effective stop rate when the intersection is operated under Actuated Control. However, the difference in performance between pretimed and actuated conditions was not found to be significant as compared to the Keshar Mahal intersection. This may be due to the difference in traffic volumes at the Durbar Marg intersection which is comparatively lower than Keshar Mahal and also the existing performance is better. It is recommended to conduct further analysis during off-peak hours for both pretimed and actuated control to confirm this.

### 3.2. Network Analysis

Simulations were conducted to evaluate different alternatives for phase configurations and cycle timing during the morning peak hour. The two best options from the intersection analysis, Option G and Option F from Keshar Mahal intersection and Option D and Option C from Durbar Marg intersection, were linked to form network options. Six routes, namely Nag Pokhari to Lainchaur, Nag Pokhari to Thamel, Nag Pokhari to Jamal, Durbar Marg to Lainchaur, Durbar Marg to Thamel, and Durbar Marg to Jamal, were selected for signal offset coordination as they have the highest traffic volume and were identified as the cause of spillback beyond the holding space.

Table 3. Network Simulations of Pretimed and Actuated Analysis

| Options | Scenario |
|---|---|
| I | Option G Keshar Mahal - Option D Durbar Marg |
| II | Option F Keshar Mahal - Option D Durbar Marg |
| III | Option G Keshar Mahal - Option C Durbar Marg |
| IV | Option F Keshar Mahal - Option C Durbar Marg |

The comparison shows that the network would function more efficiently with Option I under Pretimed Signalization, while it would perform better under Option II with Actuated Signalization.

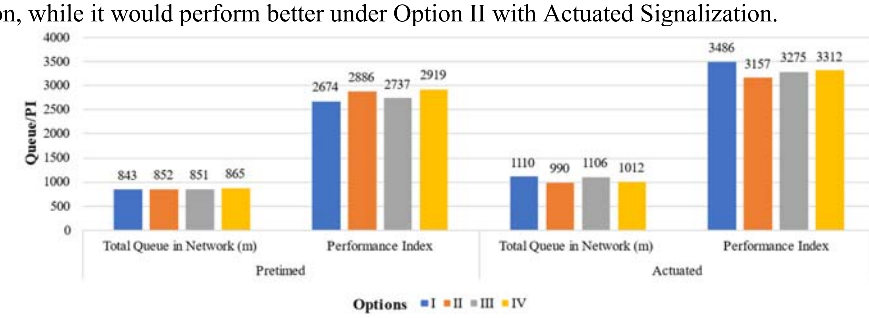



Figure 7: Total 95th percentile queue length and Performance Index in different Network simulation options

The current running intersection models of the Durbar Marg and Keshar Mahal intersection were connected to each other to form a network for analyzing the existing performance of the Keshar Mahal-Durbar Marg network. Similarly, the best results from isolated analysis were also linked to form a network to evaluate the performance of the network when it operates without signal coordination.

Table 4. Simulated Networks for Comparison

| Options | Scenario | Remarks |
|---|---|---|
| 1 | Existing Phasing (No Signal Coordination) | Existing |
| 2 | Option F Keshar Mahal - Option C Durbar Marg - Actuated (No Signal Coordination) | Best of Isolated |
| 3 | Option I (Pretimed) – (Signal Coordinated) | Best of Pretimed Signal Coordination |
| 4 | Option II (Actuated) – (Signal Coordinated) | Best of Actuated Signal Coordination |

The comparison shows that the network will perform best and have the least queue length when using the "Best of Pretimed Signal Coordination" scenario, also known as Option 3. When comparing the progression quality of Pretimed and Actuated control methods, Pretimed control was found to have better progression quality and result in improved network performance.

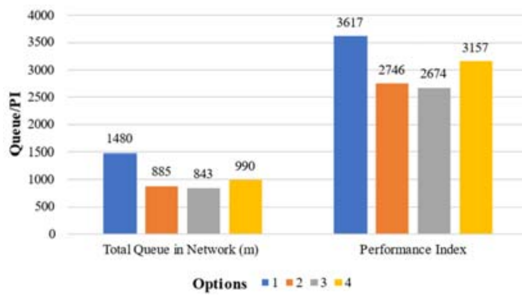



Figure 8: Performance Comparison between simulated Networks

One of the key factors that make Option 3 the most effective is the specific phase configurations of individual intersections in the network options. These configurations, which include different arrival types and platoon ratios, greatly impact the progression quality and probability of a green signal at key intersections, such as the Keshar Mahal intersection signal. Specifically, when using Option 3, the probability that vehicles traveling along the simulated routes will receive a green signal at this intersection is the highest.

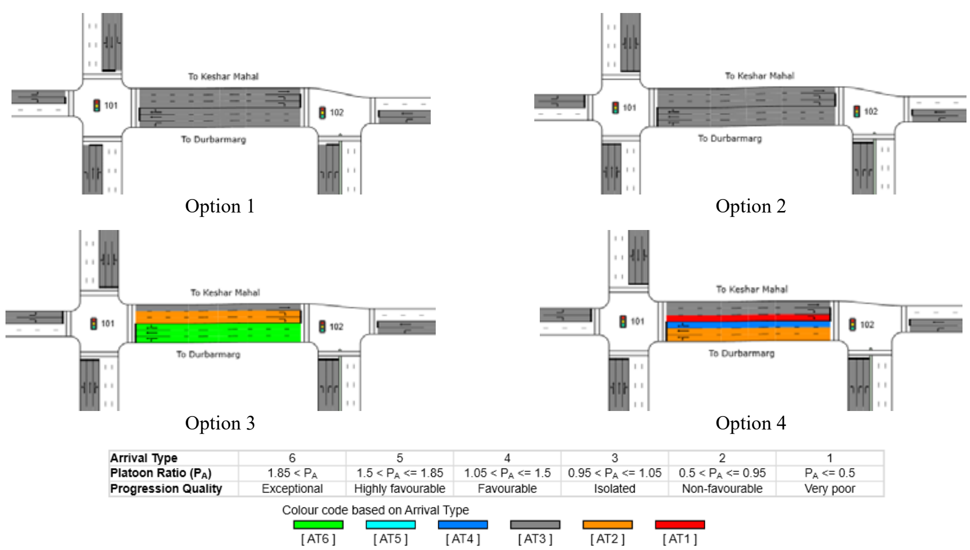
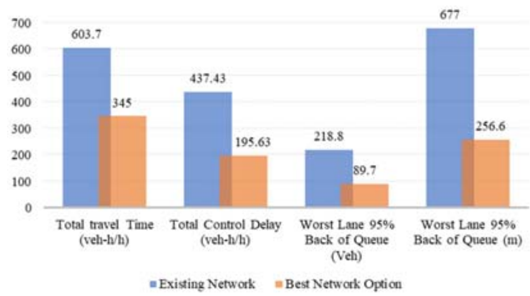


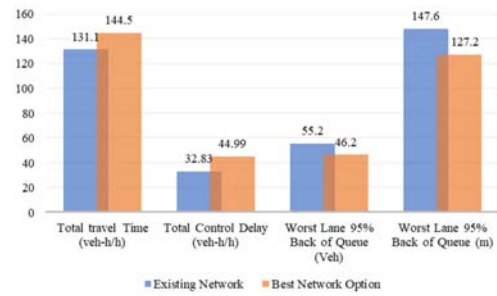

Figure 9: Arrival Type and Platoon Ratio of Simulated Network Options

### 3.3. Comparison of Existing Network with Best Network Option

The comparison of an existing network with the best simulated network option, called Option 3, shows that the best option would perform better in terms of individual performance and network performance. The best option would cause a reduction in operational performance at the Keshar Mahal intersection, with an average control delay reduction of 92.4 seconds (55.3%), an average travel time reduction of 258.7 seconds, a 95th percentile queue length reduction of 420.4 meters, and an improvement in the performance index of 1019.3 (33%). At the Durbar Marg intersection, the best option would cause a reduction in individual performance, with an average control delay increase of 12.17 seconds (37.1%), an average travel time increase of 13.3 seconds (10.2%), a 95th percentile queue length decreases of 20.5 meters (13.9%), and a worsening in the performance index of 75.9 (14.5%).




Keshar Mahal Intersection




Durbar Marg Intersection

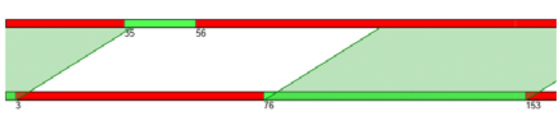
Figure 10: Intersection Performance under Existing Network and Best Network Options

However, the network as a whole would perform better with the best option, with an average travel time reduction of 245.4 seconds (33.4%), an average control delay reduction of 52.6 seconds (49.5%), and an improvement in the performance index of 943.4 (26.1%).

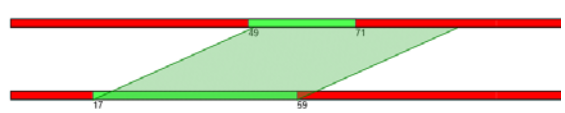
Table 5. Network Performance Comparison between Existing Network and Best Network Option

| Performance Measure | Units | Existing Network | Best Network Option | % Difference |
|---|---|---|---|---|
| Travel Speed (Average) | km/h | 10.7 | 16.1 | 50.8 |
| Travel Time (Total) | veh-h/h | 734.8 | 489.5 | -33.4 |
| Degree of Saturation | | 2.6 | 1.6 | -39.4 |
| Control Delay (Total) | veh-h/h | 470.3 | 240.6 | -48.8 |
| Control Delay (Average) | sec | 107.0 | 54.4 | -49.2 |
| Stop-Line Delay (Average) | sec | 107.0 | 54.4 | -49.2 |
| Queue Storage Ratio (Worst Lane) | | 1.0 | 0.8 | -25.1 |
| Performance Index | | 3617.3 | 2673.9 | -26.1 |

When the best Network Option is implemented, the vehicles will be able to travel along the simulated routes without interruption, resulting in better performance.



Existing Network



Best Network Option

Figure 11: Time Space Diagram in Simulated Routes

## 4. Conclusion

In this study, the traffic control systems at two intersections in Kathmandu, Nepal were analyzed and optimized. Simulations were run to determine the most effective phase configuration and signal timing strategies for both isolated and coordinated intersections using pretimed and actuated signalization. The results showed that pretimed signal coordination with an optimal network signal cycle was the most effective option. This option was compared to the existing network in terms of individual intersection performance and network-wide performance. The use of this strategy resulted in a 33.4% reduction in total travel time, a 48.8% decrease in total control delay, and an average control delay reduction of 49.2%. It also led to significant improvements in intersection performance, including a 62.1% decrease in the 95th percentile back of queue at the Keshar Mahal intersection and a 13.9% decrease at the Durbar Marg intersection.

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