AI Optimisation for Corridor Performance
iMOVE Project 1-078

Milestone 6 Report

Partners: iMOVE Australia, Cubic Transportation Systems Australia, University of Melbourne

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Executive Summary:

This report marks the culmination of iMOVE CRC Project 1-078, "AI Optimisation for Corridor Performance," a strategic collaboration between The University of Melbourne and CUBIC Transportation Systems. Initiated to address the profound and growing challenges of urban traffic congestion, this project aimed to revolutionize transport network management by validating an innovative Virtual AI-driven Traffic Management Centre (TMC). The core vision was to harness the predictive power of Artificial Intelligence (AI), Machine Learning (ML), and high-fidelity digital twin simulations to move from a reactive to a proactive paradigm of traffic control, with the ultimate goal of enhancing network efficiency, reducing travel times, and improving the movement of people and goods across Melbourne.

The project's foundation was meticulously constructed through a multi-faceted data and modelling strategy. A significant methodological effort was dedicated to the collection, curation, and integration of two disparate, high-volume data streams: Sydney Coordinated Adaptive Traffic System (SCATS) data, providing granular traffic volume, detector counts, and signal phase information; and TomTom Live Speed data, offering real-time insights into traffic flow and speed dynamics across the network. This synthesized dataset provided the rich, multi-dimensional ground truth necessary for validating robust AI models and calibrating a realistic simulation environment.

A cornerstone of this initiative was the creation of a high-fidelity digital twin of a key Melbourne road network, developed using the PTV VISSIM microscopic simulation software. This digital twin encompasses 28 signalized intersections and models complex traffic behaviours, including dynamic route choice and actuated signal control. It served as a critical, risk-free virtual environment for rigorously testing and validating a wide array of traffic management interventions that would be impractical or disruptive to trial on the live network.

The technical core of the project involved the retrofitting, extensive testing, and refinement of advanced time-series forecasting models, primarily focusing on Long Short-Term Memory (LSTM) networks and the advanced transformer-based Informer model. Our extensive analysis yielded several key findings:

- Model Specialization: LSTM models consistently provide superior accuracy for short-term forecasting (horizons ≤15 minutes), making them ideal for immediate, tactical traffic management responses. Conversely, the Informer model's architecture proved

more effective for long-term forecasting (≥30 minutes), demonstrating its capacity for more strategic, forward-looking network planning.

- Hyperparameter Optimization: The project validated the significant performance gains achieved through sophisticated hyperparameter tuning. Techniques such as Bayesian Optimization were shown to deliver better-optimized models more efficiently than traditional Grid Search methods, leading to notable improvements in predictive accuracy.
- Resilience and Adaptability: The models' robustness was critically evaluated against non-recurring events, such as traffic incidents and simulated road closures. While performance degradation is expected during such anomalies, the analysis provided crucial insights into model behaviour under stress. Furthermore, a framework for Continuous Learning was established, proving that periodically retraining models with the most recent data is essential for maintaining high accuracy as underlying traffic patterns and network conditions evolve over time.

Leveraging this powerful combination of AI and simulation, the project conducted a comprehensive analysis of 36 distinct traffic scenarios within the digital twin. These scenarios explored the network-wide impacts of interventions ranging from signal timing modifications and speed limit adjustments to full and partial road closures. This systematic evaluation provided invaluable, data-driven insights. A principal finding was the quantifiable superiority of fully-actuated signal timing over fixed-time systems in mitigating congestion, particularly during peak hours. The simulations also illuminated the complex ripple effects of localized interventions, underscoring the necessity of a holistic, network-aware management approach.

In conclusion, Project 1-078 has successfully delivered a validated framework and a strategic blueprint for the next generation of traffic management. Based on the robust evidence gathered, this report puts forward a series of actionable recommendations designed to translate the project's findings into tangible benefits for Melbourne:

1. Enhance Real-Time Prediction Capabilities: Integrate the validated LSTM and into existing TMC platforms to provide operators with accurate short- and long-term traffic forecasts, enabling proactive decision-making.
2. Stress-Testing AI platform with Advanced Simulations: Utilize the developed digital twin as an ongoing strategic planning tool to assess the potential impacts of future

infrastructure projects, urban developments, and policy changes before implementation.

3. Implement Data-Driven, Adaptive Strategies: Leverage the insights from the scenario analyses to develop dynamic traffic management plans that can adapt in real-time to changing network conditions, balancing traffic loads more efficiently across corridors.

This project has not only achieved its technical objectives but has also laid the essential groundwork for a smarter, more responsive, and more efficient urban transportation ecosystem. The methodologies and technologies validated herein offer a clear path forward for Melbourne to effectively manage the complexities of urban growth and mobility.

A regular fine-tuning for the existing LSTM is strongly recommended. All the models and fine-tuning code have already been provided with Cubic

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Section Report: Testing Virtual AI-driven TMC

1. Introduction

As urban areas grapple with escalating traffic congestion and the pressing need for sustainable transportation solutions, the development of advanced traffic management systems has become increasingly critical. This section explores the comprehensive testing of a virtual AI-driven Traffic Management Center (TMC), integrating the developed AI model and digital twin. Based on the results of a series of scenarios, analysis has been conducted, with findings and insights presented.

We employ a Long Short-Term Memory (LSTM) network as the core predictive engine within the virtual TMC. LSTM is a type of recurrent neural network (RNN) particularly well-suited for learning from sequential data, making it effective for capturing temporal dependencies inherent in traffic patterns. Unlike traditional RNNs, LSTM mitigates issues of vanishing gradients through its gating mechanisms, enabling it to retain long-term contextual information. In the context of traffic forecasting, the model is trained on historical traffic flow data to anticipate short-term variations in vehicle speeds and volumes across key road segments. By doing so, it enables real-time decision support and scenario analysis within the digital twin environment, enhancing the system's ability to respond dynamically to evolving traffic conditions.

The digital twin development leverages PTV VISSIM, a leading microscopic traffic simulation software widely recognized in transportation engineering, to evaluate the system's performance across a diverse array of scenarios. Based on the simulation results, a detailed analysis has been conducted, yielding key findings and actionable insights into traffic network dynamics.

Specifically, 36 scenarios are designed and implemented in VISSIM, encompassing a broad spectrum of TMC control measures, including a wide range of signal timing revisions and speed limit settings. Changes made in scenarios vary in simulation duration and are applied to both peak and non-peak hours, and also span multiple spatial scales, from single intersections to multi-corridor. This diversity ensures that the virtual TMC is rigorously evaluated, mirroring the complexities of urban traffic systems.

Meanwhile, the performance of AI model in traffic states forecasting are evaluated using VISSIM simulation outputs as ground truth. Two distinct forecasting strategies are employed: Pure Historical Forecasting, which relies exclusively on historical traffic data to predict future states, and Ground Truth Enhanced Forecasting, which integrates real-time data into model input to enhance prediction accuracy. To assess their performance, 12 carefully crafted test cases are analysed, covering a wide range of traffic state change magnitudes and traffic network changes. These test aims to provide a comprehensive understanding of AI model's robustness and adaptability.

This testing significantly enhances our understanding of the digital twin and AI forecasting model's characteristics, while delivering practical insights into traffic management. By simulating a wide range of scenarios, the analysis reveals how traffic networks perform and maintain resilience under varying conditions, and identifies general strategies for improving overall system performance. The evaluation of the AI model further sheds light on its performance and highlights potential areas for enhancement. Ultimately, these findings contribute to the development of intelligent transportation systems and support broader smart city initiatives.

Through this detailed exploration, this section sets the stage for a deeper dive into the methodology, results, and implications of virtual AI-driven TMC evaluation. It underscores the transformative potential of combining AI and digital twins, paving the way for a future where technology seamlessly integrates with transportation to address the challenges of urbanization.

2. Methodology

2.1. Digital twin development

As introduced previously, we developed a large-scale microscopic simulation model that acts as a digital twin for a real-world traffic network, specifically focusing on vehicular traffic. The network includes 28 signalized intersections composed of various minor and major roads, accommodating a high volume of vehicles. Figure 1 provides an overview of the simulated network, highlighted in red.

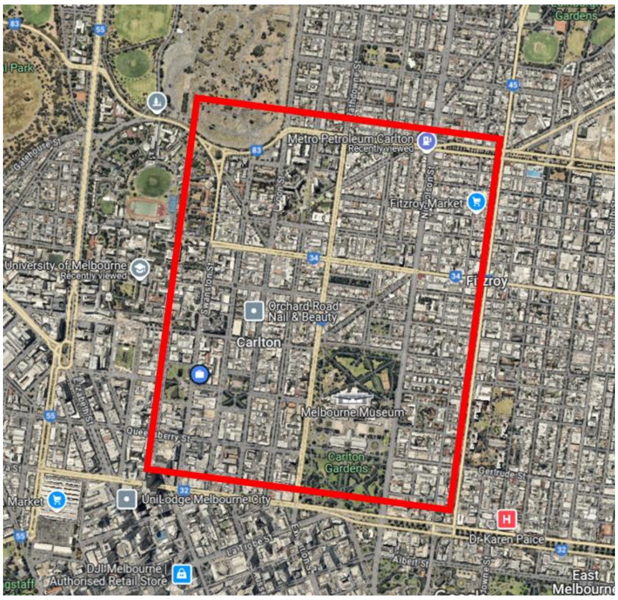


Figure 1: An overview of the simulated network (marked in red).

The simulation model used VISSIM. Specifically, the network was established by using aerial images of the real-world road network as a reference to design a simplified yet accurate model. Links and connectors were employed to draw the network, replicating the road layout, allowable turns at intersections, and the number of lanes at specific locations. To monitor traffic flow, loop detectors were positioned at the stop bars in each direction. Several measures are conducted to reduce complexity, such as very minor roads were excluded from the model, ensuring the network closely resembles the real-world configuration while maintaining manageable detail. A uniform speed of 50 km/h is applied throughout the network, reflecting typical urban road conditions. Give-way rules to the conflicting areas are also designed.

Signal settings were configured in VISSIM using the signal controller list and the "Vissig" tool. For actuated signal timing, we employed VAP (Vehicle Actuated Programming) in conjunction with the visual programming tool VisVAP. VisVap also serves as a tool for implementing signal setting changes at specific times during the simulation. Specifically, for the 2-hour simulations, any changes to signal settings were implemented at the end of the first hour to emulate short-term control by the TMC.

Realistic traffic demands were incorporated into the simulation. These demands were extracted from SCATS loop detector volume data, which provides accurate measurements of real-world traffic flows. After making reasonable adjustments, the data was input into VISSIM in the form of Origin-Destination matrices, which were then used for trip generation.

To model the dynamic nature of traffic and route choice behaviour, Dynamic Assignment was adopted. Several strategies were implemented to enhance convergence performance, including limiting the simulation period, extending the evaluation time to 30 minutes, initiating Dynamic Assignment with 20% of the demand and incrementally increasing it by 5% each iteration, prohibiting long detours, and disabling adaptive behaviours. Dynamic Assignment is rerun when significant network modifications are applied, such as substantial speed limit increases (e.g., from 50 km/h to 80 km/h), to recalibrate route choices and reflect updated traffic behavior.

For analyzing the simulation results, the output vehicle record files generated by VISSIM were utilized.

2.2. AI model forecasting

There are N sensors in a traffic system (i.e., area). For each sensor i, we use $x_{i,t} \in R^C$ to represent the traffic observation record of i at time step t, where C is the number of types of observations, e.g., traffic flow and traffic speed. Further, $\boldsymbol{X}_t = [x_{1,t}, x_{2,t}, \dots, x_{N,t}] \in R^{N \times C}$ denotes the observations of all sensors in the traffic system at time step t, while $\widehat{\boldsymbol{X}}_t \in R^{N \times C}$ to denote the forecasts of the sensors at time step t. We use $\boldsymbol{X}_{t_i:t_j}$ to denote the consecutive observations from t_i to t_j, i.e., $[\boldsymbol{X}_{t_i}, \dots, \boldsymbol{X}_{t_j}]$.

Problem Statement. Given a T-step historical traffic observations, a traffic forecasting model aims to forecast the future T'-step traffic observations: $[\boldsymbol{X}_{t-T+1}, \dots, \boldsymbol{X}_t] \xrightarrow{f(\cdot)} [\widehat{\boldsymbol{X}}_{t+1}, \dots, \widehat{\boldsymbol{X}}_{t+T'}]$

In TMC, we utilize a Long Short-Term Memory (LSTM) network to capture temporal dependencies within each sensor's time series. Notably, all sensors share a single LSTM model, which processes each node's historical sequence independently—this design focuses on learning temporal dynamics but does not explicitly model correlations among different sensors. This trade-off allows the model to scale efficiently across large networks, although spatial interactions are not directly considered within the LSTM layer.

Each input vector is composed of four features: (i) current traffic condition (flow/speed), (ii) day-of-week indicator (0–6), (iii) time-of-day slot (0–95, dividing 24 hours into 96 slots), and (iv) free flow speed. The free flow speed for each sensor is computed as the 85th percentile of observed speeds during non-peak hours (9:00–16:00 and 22:00–6:00), following established practices. These four components are concatenated and used as the input at each time step, providing temporal, contextual, and static information to guide the forecasting process.

2.2.1. AI model implementation

We adopt **a two-stage framework** for LSTM in TM. In the first stage, we train the model on real-world traffic data collected from urban sensors in Melbourne, and in the second stage, we test the trained model within a simulation environment using virtual sensor data generated by the digital twin. The rationale behind this two-stage approach lies in data availability: the amount of simulated data is insufficient to support training a data-driven model effectively, whereas the real-world dataset offers sufficient volume and diversity for model learning.

For model training, we use the previous one hour of traffic records—equivalent to four time steps sampled at 15-minute intervals—as input to predict traffic speed (or volume) over the next 15, 30, 45, and 60 minutes. Consistent with the settings used in the released Cubic benchmark, we divide the dataset temporally, using the first 80% of the data for training and the last 20% for testing.

The LSTM model takes four input features as mentioned above per sensor at each time step. Two key hyperparameters—learning rate and the number of hidden units—are optimised via grid search to ensure balanced model capacity and generalisation. Extensive experiments were conducted on the self-collected Melbourne datasets to determine optimal configurations. For both traffic volume and traffic speed, we adopts learning rate 1e-3 and hidden layer 64 for training LSTM.

2.2.2. Forecasting method

Two commonly adopted strategies in practice are implemented and assessed, namely, Pure Historical Forecasting (hereafter referred to as Forecasting Strategy 1) and Ground Truth Enhanced Forecasting (hereafter referred to as Forecasting Strategy 2). These two strategies are described in detail below.

As illustrated in Figure 2, Forecasting Strategy 1 (Pure Historical Forecasting) adopts a multi-step forecasting approach that relies solely on past traffic data to predict future traffic conditions. Specifically, the model takes the traffic measurements from the previous four time steps as input and generates predictions for the next four time steps. This strategy assumes that all future values are unknown at prediction time and must be inferred purely from historical patterns. Due to its reliance exclusively on past data, this method is straightforward to implement and does not require access to real-time or future information. However, its simplicity comes with limitations: the model is prone to the accumulation of prediction errors over multiple steps, and it may struggle to adapt to sudden or unexpected changes in traffic conditions, such as incidents or demand spikes.

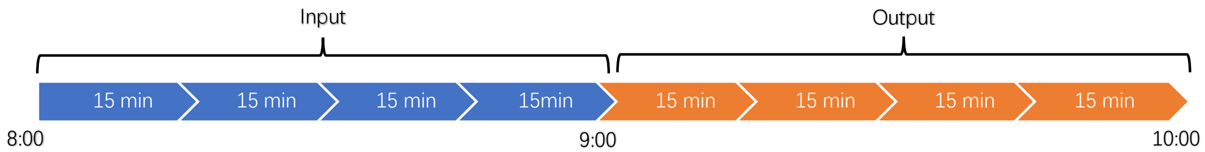


Figure 2: Forecasting scheme of the Pure Historical Forecasting strategy.

In contrast, Forecasting Strategy 2 (Ground Truth Enhanced Forecasting) enhances the input sequence by injecting actual observed values from within the prediction horizon into the model's input, as illustrated in Figure 3). While it also begins with the same four historical time steps as a base, it supplements the input with ground truth values of future steps before proceeding to predict further time steps. For instance, when forecasting traffic for the sixth to eighth time steps, the model is provided with the actual value of the fifth step (i.e., the first within the forecast horizon) to improve accuracy. This approach helps mitigate the propagation of forecasting errors, and the use of real observed data enables the model to better capture rapidly changing traffic dynamics. Nevertheless, the effectiveness of this strategy depends heavily on the availability and reliability of real-time or near-future traffic data. Additionally, in operational settings where such data is accessible, the approach effectively enables single-step forecasting at each stage, thereby reducing long-term prediction drift and enhancing robustness.

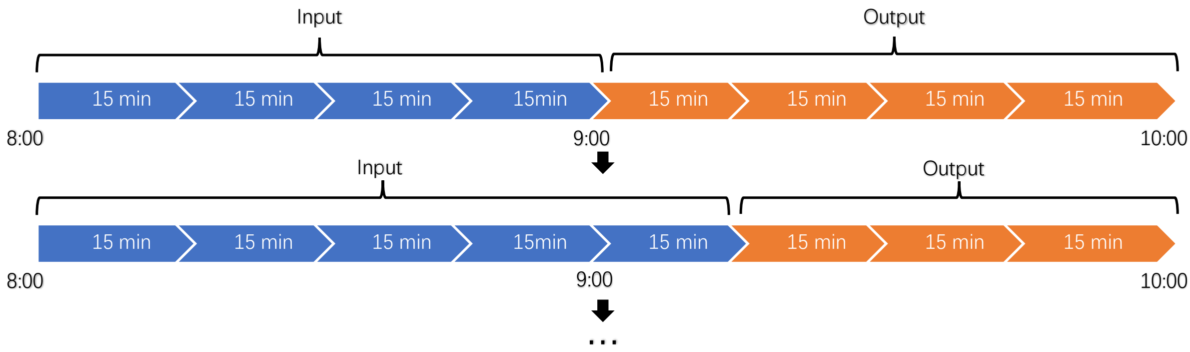


Figure 3: Forecasting scheme of the Ground Truth Enhanced Forecasting strategy.

3. Results and discussion

3.1. Scenario Information and Results for Digital Twin

This section provides a detailed description of each scenario along with the corresponding results. For the results, the average changes in traffic volume and speed are calculated relative to their respective baselines. The baseline cases include simulations for a 1-hour peak period, a 2-hour peak period, and a 2-hour non-peak period, all using fully-actuated signal timing when applicable. The average volume and speed for each base case are summarised in Table 1. Additionally, an overview of each scenario is provided in Table 20.

Table 1 Results for base cases.

Base case setting	1-hour peak-hour (8:30–9:30)	2-hour peak-hour (8:00–10:00)	2-hour non-peak-hour (21:00–23:00)
Average Volume (Veh/15mins)	143.93	141.26	60.32
Average speed (km/h)	24.62	22.47	31.92

3.1.1. Scenario 1

- **Description:** Change the specified intersection's signal timing from fully-actuated signal timing to fixed-time signal timing during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 144.36
    - Average speed (km/h): 24.02
    - Average volume change: 0.3% increase
    - Average speed change: 2.47% decrease

3.1.2. Scenario 2

- **Description:** Change the specified multiple intersections' signal timing from fully-actuated signal timing to fixed-time signal timing during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 141.58
    - Average speed (km/h): 22.62
    - Average volume change: 1.64% decrease
    - Average speed change: 8.15% decrease

3.1.3. Scenario 3

- **Description:** Change the specified intersection's signal timing from fully-actuated signal timing to fixed-time signal timing during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 144.15
    - Average speed (km/h): 24.56
    - Average volume change: 0.15% increase
    - Average speed change: 0.26% decrease

3.1.4. Scenario 4

- **Description:** Change the specified multiple intersections' signal timing from fully-actuated signal timing to fixed-time signal timing during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 140.13
    - Average speed (km/h): 24.01
    - Average volume change: 2.65% decrease
    - Average speed change: 2.48% decrease

3.1.5. Scenario 5

- **Description:** Change the specified multiple intersections' signal timing from fully-actuated signal timing to fixed-time signal timing during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 143.08
    - Average speed (km/h): 24.68
    - Average volume change: 0.6% decrease
    - Average speed change: 0.24% increase

3.1.6. Scenario 6

- **Description:** Reduce the speed limit of the designated road section from 50 km/h to 20 km/h during the morning peak hour on a workday (8:30–9:30).
- **Results:**
    - Average Volume (Veh/15mins): 147.4
    - Average speed (km/h): 22.87
    - Average volume change: 2.41% decrease
    - Average speed change: 7.13% decrease

3.1.7. Scenario 7

- **Description:** Adjust the signal timing of the specified intersection by increasing or decreasing the maximum green time for all stages by 50% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**

  See Table 2.

Table 2 Results for Scenario 7

	Maximum green time increase	**Maximum green time decrease**
Average Volume (Veh/15mins)	142	145.58
Average speed (km/h)	24.49	24.46
Average volume change	1.34% decrease	1.15% increase
Average speed change	0.54% decrease	0.64% decrease

3.1.8. Scenario 8

- **Description:** Adjust the signal timing of the specified intersection by increasing or decreasing the gap time for all stages by 50% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**

  See Table 3.

Table 3 Results for Scenario 8

	Gap time increase	Gap time decrease
Average Volume (Veh/15mins)	143.89	143.09
Average speed (km/h)	24.67	24.33
Average volume change	0.03% decrease	0.59% decrease
Average speed change	0.17% increase	1.18% decrease

3.1.9. Scenario 9

- **Description:** Adjust the signal timing of the specified intersection by increasing or decreasing the maximum green time for all stages by 50% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**

  See Table 4.

Table 4 Results for Scenario 9

	Maximum green time increase	Maximum green time decrease
Average Volume (Veh/15mins)	143.84	143.97
Average speed (km/h)	24.65	24.44
Average volume change	0.07% decrease	0.03% increase
Average speed change	0.11% increase	0.74% decrease

3.1.10. Scenario 10

- **Description:** Adjust the signal timing of the specified intersection by increasing or decreasing the gap time for all stages by 50% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**

  See Table 5.

Table 5 Results for Scenario 10

	Gap time increase	Gap time decrease
Average Volume (Veh/15mins)	143.89	144.77
Average speed (km/h)	24.58	24.67
Average volume change	0.03% decrease	0.58% increase
Average speed change	0.17% decrease	0.18% increase

3.1.11. Scenario 11

- **Description:** Adjust the signal timing of the specified intersection by increasing the maximum green time of only the stage with higher traffic volume (EW) by 50% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**
  - Average Volume (Veh/15mins): 144.8
  - Average speed (km/h): 24.77
  - Average volume change: 0.6% increase
  - Average speed change: 0.61% increase

3.1.12. Scenario 12

- **Description:** Adjust the signal timing of the specified intersection by increasing the maximum green time of only the stage with higher traffic volume (EW) by 100% during the morning peak hour (8:30–9:30) on a workday.
- **Results:**
  - Average Volume (Veh/15mins): 139.57
  - Average speed (km/h): 24.6
  - Average volume change: 3.03% decrease
  - Average speed change: 0.08% decrease

3.1.13. Scenario 13

- **Description:** Adjust the signal timing of the specified intersection by gradually increasing the maximum green time of only the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 6.

Table 6 Results for Scenario 13

	10% maximum green time increase	20% maximum green time increase	50% maximum green time increase
Average Volume (Veh/15mins)	138.42	136.76	140.03
Average speed (km/h)	22.22	22.33	22.53
Average volume change	2.01% decrease	3.19% decrease	0.87% decrease
Average speed change	1.13% decrease	0.65% decrease	0.27% increase

3.1.14. Scenario 14

- **Description:** Adjust the signal timing of the specified intersection by gradually increasing the gap time of only the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 7.

Table 7 Results for Scenario 14

	Adding 0.5s gap time	Adding 1.0s gap time
Average Volume (Veh/15mins)	141.26	141.26
Average speed (km/h)	22.47	22.47
Average volume change	No change	No change
Average speed change	No change	No change

3.1.15. Scenario 15

- **Description:** Adjust the signal timing of the specified intersection by gradually decreasing the maximum green time of only the stage with lower traffic volume (NS) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 8.

Table 8 Results for Scenario 15

	10% maximum green time decrease	20% maximum green time decrease	50% maximum green time decrease

Average Volume (Veh/15mins)	137.55	137.18	139.68
Average speed (km/h)	22.39	22.23	22.63
Average volume change	2.63% decrease	2.89% decrease	1.12% decrease
Average speed change	0.37% decrease	1.09% decrease	0.70% increase

3.1.16. Scenario 16

- **Description:** Adjust the signal timing of the specified intersection by gradually decreasing the gap time of only the stage with lower traffic volume (NS) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 9.

Table 9 Results for Scenario 16

	Reducing 0.5s gap time	Reducing 1.0s gap time
Average Volume (Veh/15mins)	140.29	138.48
Average speed (km/h)	22.29	22.49
Average volume change	0.69% decrease	1.97% decrease
Average speed change	0.80% decrease	0.07% increase

3.1.17. Scenario 17

- **Description:** Adjust the signal timing of the multiple (1 corridor) specified intersections by gradually increasing the maximum green time of only the generally major direction (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 10.

Table 10 Results for Scenario 17

	10% maximum green time increase	20% maximum green time increase	50% maximum green time increase
Average Volume (Veh/15mins)	139.62	139.92	139.05
Average speed (km/h)	22.36	22.51	22.47
Average volume change	1.16% decrease	0.95% decrease	1.56% decrease
Average speed change	0.52% decrease	0.17% increase	0.03% decrease

3.1.18. Scenario 18

- **Description:** Adjust the signal timing of the multiple (1 corridor) specified intersections by gradually increasing the maximum green time of all stages during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 11.

Table 11 Results for Scenario 18

	10% maximum green time increase	20% maximum green time increase	50% maximum green time increase
Average Volume (Veh/15mins)	140.22	138.81	137.23
Average speed (km/h)	22.48	22.43	22.52
Average volume change	0.74% decrease	1.74% decrease	2.85% decrease
Average speed change	0.04% increase	0.19% decrease	0.19% increase

3.1.19. Scenario 19

- **Description:** Adjust the signal timing of the multiple (2 corridors) specified intersections by gradually increasing the maximum green time of all stages during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 12.

Table 12 Results for Scenario 19

	10% maximum green time increase	20% maximum green time increase	50% maximum green time increase
Average Volume (Veh/15mins)	138.06	141.05	141.67
Average speed (km/h)	22.45	22.47	22.53
Average volume change	2.27% decrease	0.15% decrease	0.29% increase
Average speed change	0.12% decrease	0.005% increase	0.26% increase

3.1.20. Scenario 20

- **Description:** Adjust the signal timing of the specified intersection by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**
  - Average Volume (Veh/15mins): 138.24
  - Average speed (km/h): 22.24
  - Average volume change: 2.13% decrease
  - Average speed change: 1.05% decrease

3.1.21. Scenario 21

- **Description:** Adjust the signal timing of the specified intersection by changing the signal timing from fully-actuated signal timing to fixed-time signal timing and gradually increasing the green time of only the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 13.

Table 13 Results for Scenario 21

	3s green time increase	5s green time increase	10s green time increase
Average Volume (Veh/15mins)	138.09	140.91	139.17
Average speed (km/h)	22.21	22.35	22.35
Average volume change	2.24% decrease	0.25% decrease	1.48% decrease
Average speed change	1.17% decrease	0.53% decrease	0.55% decrease

3.1.22. Scenario 22

- **Description:** Adjust the signal timing of multiple (1 corridor) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**
  - Average Volume (Veh/15mins): 137.27

- Average speed (km/h): 22.16
- Average volume change: 2.82% decrease
- Average speed change: 1.37% decrease

3.1.23. Scenario 23

- **Description:** Adjust the signal timing of multiple (1 corridor) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing and gradually increasing the green time of only the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**

  See Table 14.

Table 14 Results for Scenario 23

	3s green time increase	5s green time increase	10s green time increase
Average Volume (Veh/15mins)	138.77	140.22	138.56
Average speed (km/h)	22.22	22.26	22.34
Average volume change	1.76% decrease	0.74% decrease	1.91% decrease
Average speed change	1.14% decrease	0.97% decrease	0.58% decrease

3.1.24. Scenario 24

- **Description:** Adjust the signal timing of multiple (2 corridors) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday.
- **Results:**
  - Average Volume (Veh/15mins): 128.06
  - Average speed (km/h): 21.91
  - Average volume change: 9.35% decrease
  - Average speed change: 2.53% decrease

3.1.25. Scenario 25

- **Description:** Adjust the signal timing of the single and multiple (1 corridor) specified intersections by increasing the maximum green time by 50% of only the stage with higher traffic volume (EW) during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See Table 15.

Table 15 Results for Scenario 25

	Single intersection	Multiple (1 corridor) intersections
Average Volume (Veh/15mins)	60.32	60.32
Average speed (km/h)	31.92	31.92
Average volume change	No change	No change
Average speed change	No change	No change

3.1.26. Scenario 26

- **Description:** Adjust the signal timing of the multiple (2 corridors) specified intersections by gradually increasing the maximum green time of all stages during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See Table 16.

Table 16 Results for Scenario 26

	10% maximum green time increase	20% maximum green time increase	50% maximum green time increase
Average Volume (Veh/15mins)	60.35	60.37	60.35
Average speed (km/h)	31.93	32.01	31.97
Average volume change	0.05% increase	0.08% increase	0.04% increase
Average speed change	0.03% increase	0.28% increase	0.16% increase

3.1.27. Scenario 27

- **Description:** Adjust the signal timing of the specified intersection by gradually increasing the gap time of only the stage with higher traffic volume (EW) during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See Table 17.

Table 17 Results for Scenario 27

	Adding 0.5s gap time	Adding 1.0s gap time
Average Volume (Veh/15mins)	60.28	60.24
Average speed (km/h)	32.01	31.98
Average volume change	0.08% decrease	0.14% decrease
Average speed change	0.28% increase	0.18% increase

3.1.28. Scenario 28

- **Description:** Adjust the signal timing of the specified intersection by gradually decreasing the gap time of only the stage with lower traffic volume (NS) during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See Table 18.

Table 18 Results for Scenario 28

	Reducing 0.5s gap time	Reducing 1.0s gap time
Average Volume (Veh/15mins)	60.31	60.32
Average speed (km/h)	31.88	31.85
Average volume change	0.03% decrease	0.003% decrease
Average speed change	0.13% decrease	0.21% decrease

3.1.29. Scenario 29

- **Description:** Adjust the signal timing of multiple (1 corridor) intersections by gradually increasing the gap time of only the stage with higher traffic volume (EW) during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See Table 19.

Table 19 Results for Scenario 29

	Adding 0.5s gap time	Adding 1.0s gap time
Average Volume (Veh/15mins)	60.37	60.34
Average speed (km/h)	31.86	31.95
Average volume change	0.08% increase	0.02% increase
Average speed change	0.20% decrease	0.11% increase

3.1.30. Scenario 30

- **Description:** Adjust the signal timing of multiple (2 corridors) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 60.04
    - Average speed (km/h): 31.09
    - Average volume change: 0.46% decrease
    - Average speed change: 2.59% decrease

3.1.31. Scenario 31

- **Description:** Increase the speed limit of the corridor with heavier flow to 80 km/h during the morning peak hour (8:00–10:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 146.26
    - Average speed (km/h): 24.03
    - Average volume change: 3.54% increase
    - Average speed change: 6.94% increase

3.1.32. Scenario 32

- **Description:** Increase the speed limit of the corridor with lighter flow to 80 km/h during the morning peak hour (8:00–10:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 140.77
    - Average speed (km/h): 22.79
    - Average volume change: 0.34% decrease
    - Average speed change: 1.41% increase

3.1.33. Scenario 33

- **Description:** Decrease the speed limit of the corridor with heavier flow to 40 km/h during morning peak hour (8:00–10:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 141.95
    - Average speed (km/h): 22.63
    - Average volume change: 0.49% increase
    - Average speed change: 0.68% increase

3.1.34. Scenario 34

- **Description:** Decrease the speed limit of the corridor with heavier flow to 40 km/h during the non-peak hour (21:00–23:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 60.39
    - Average speed (km/h): 31.63
    - Average volume change: 0.12% increase
    - Average speed change: 0.92% decrease

3.1.35. Scenario 35

- **Description:** Decrease the speed limit of the corridor with lighter flow to 40 km/h during the morning peak hour (8:00–10:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 140.06
    - Average speed (km/h): 22.21
    - Average volume change: 0.85% decrease
    - Average speed change: 1.18% decrease

3.1.36. Scenario 36

- **Description:** Decrease the speed limit of the corridor with lighter flow to 40 km/h during the non-peak hour (21:00–23:00) on a workday.
- **Results:**
    - Average Volume (Veh/15mins): 60.26
    - Average speed (km/h): 31.74
    - Average volume change: 0.11% decrease
    - Average speed change: 0.57% decrease

Table 20: Demonstrations of changes applied to the simulated network in each scenario, including the simulation period and scenario number

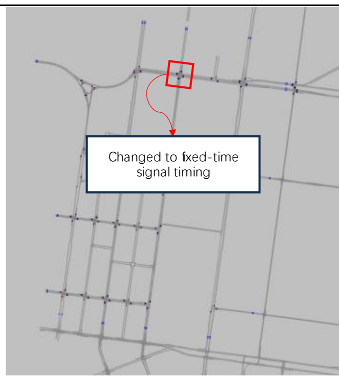
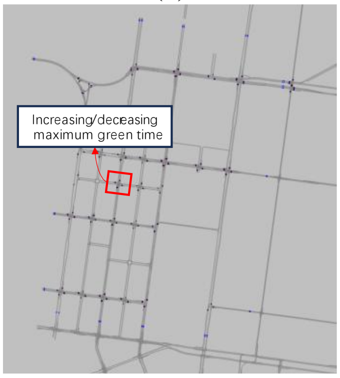
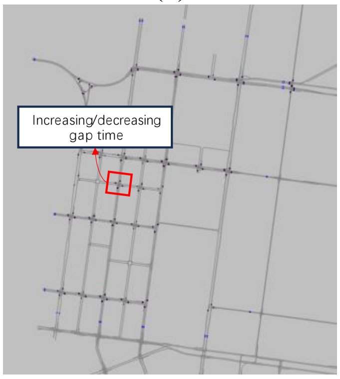
 8:30–9:30 (1)	 8:30–9:30 (2)	 8:30–9:30 (3)
 8:30–9:30 (4)	 8:30–9:30 (5)	 8:30–9:30 (6)
 8:30–9:30 (7)	 8:30–9:30 (8)	 8:30–9:30 (9)
 8:30–9:30 (10)	 8:30–9:30 (11)	 8:30–9:30 (12)

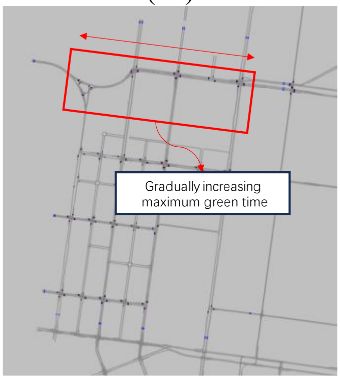
Table 3: Continued

9:00–10:00 of 8:00–10:00
(13)

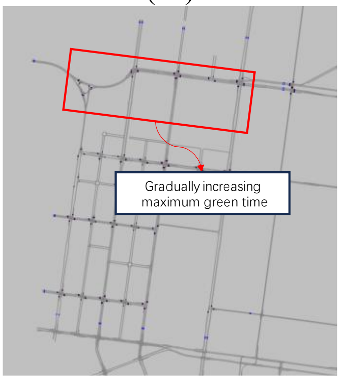
9:00–10:00 of 8:00–10:00
(14)

9:00–10:00 of 8:00–10:00
(15)

9:00–10:00 of 8:00–10:00
(16)



9:00–10:00 of 8:00–10:00
(17)

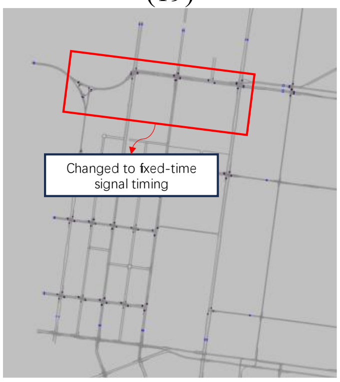


9:00–10:00 of 8:00–10:00
(18)

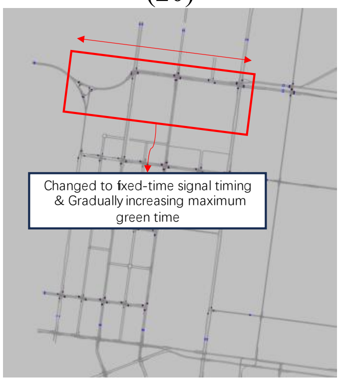
9:00–10:00 of 8:00–10:00
(19)

9:00–10:00 of 8:00–10:00
(20)

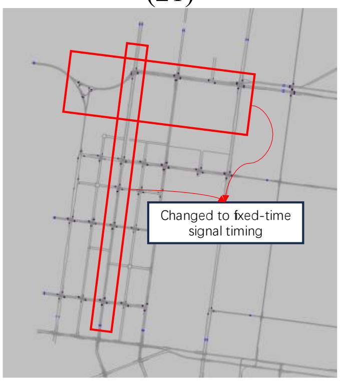
9:00–10:00 of 8:00–10:00
(21)



9:00–10:00 of 8:00–10:00
(22)



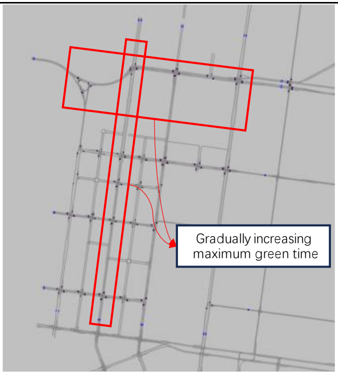
9:00–10:00 of 8:00–10:00
(23)



9:00–10:00 of 8:00–10:00
(24)

Table 3: Continued

22:00–23:00 of 21:00–23:00
(25)

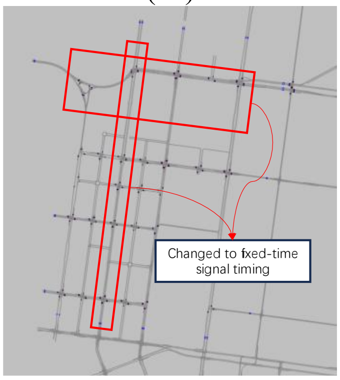


22:00–23:00 of 21:00–23:00
(26)

22:00–23:00 of 21:00–23:00
(27)

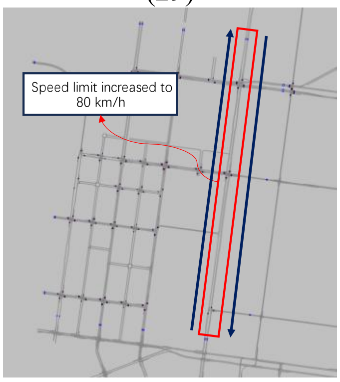
22:00–23:00 of 21:00–23:00
(28)

22:00–23:00 of 21:00–23:00
(29)



22:00–23:00 of 21:00–23:00
(30)

8:00–10:00
(31)

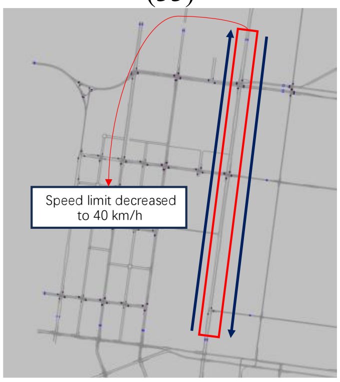


8:00–10:00
(32)

8:00–10:00
(33)

21:00–23:00
(34)

8:00–10:00
(35)



21:00–23:00
(36)

3.2. Evaluation Information and Results for AI model

This section presents 12 testing cases for the AI model, using ground truth data collected from selected digital twin simulation scenarios out of a total of 36. The purpose is to understand the AI model's accuracy and adaptability when adopting the two forecasting strategies across a wide range of TMC control, applied to the simulated traffic network. The test is conducted in predicting traffic conditions every 15 minutes, ensuring its suitability for real-time applications. Two metrics are adopted, including MAE and MSE, which are defined as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |y_i - \hat{y}_i|. \quad (1)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_i)^2. \quad (2)$$

3.2.1. Peak hour base case

- **Description:** Base case for AI model forecasting during the morning peak hour on a workday 8:00–10:00, the forecasting window is 9:00–10:00.
- **Results:**

  See Table 21.

Table 21 Results for peak hour base case

Traffic Condition	Strategy	Forecasting Results	
		Network MAE	Network MSE
Volume	Strategy 1	32.013	2061.923
	Strategy 2	24.929	1315.388
Speed	Strategy 1	5.97	65.54
	Strategy 2	4.402	34.69

3.2.2. Case 1

- **Description:** This case corresponds to the scenario where the signal timing at the specified intersection is adjusted by increasing the maximum green time by 10% for the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of the morning peak period (8:00–10:00) on a workday. This adjustment results in a 2.01% decrease in average volume and a 1.13% decrease in average speed.
- **Results:**

  See Table 22.

Table 22 Results Case 1

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	33.541; 4.77%	2499.375; 21.22%
	Strategy 2	30.168; 21.02%	1966.993; 49.54%
Speed	Strategy 1	6.455; 8.11%	76.854; 17.26%
	Strategy 2	4.776; 8.52%	43.007; 23.97%

3.2.3. Case 2

- **Description:** Adjust the signal timing of the specified intersection by increasing the maximum green time by 50% of only the stage with higher traffic volume (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday. Resulting in 0.87% average volume decrease and 0.27% average speed increase.
- **Results:**

  See 23.

Table 23 Results Case 2

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	31.681; -1.04%	2062.542; 0.03%
	Strategy 2	26.553; 6.51%	1398.426; 6.31%
Speed	Strategy 1	6.043; 1.21%	64.000; -2.35%
	Strategy 2	4.445; 1.01%	33.984; -2.04%

3.2.4. Case 3

- **Description:** Adjust the signal timing of the multiple (1 corridor) specified intersections by increasing the maximum green time by 50% of only the generally major direction (EW) during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday. Resulting in 1.56% average volume decrease and 0.03% average speed decrease.
- **Results:**

  See 24.

Table 24 Results Case 3

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	31.097; -2.86%	1982.778; -3.84%
	Strategy 2	25.792; 3.46%	1284.952; -2.31%
Speed	Strategy 1	6.061; 1.53%	66.750; 1.85%
	Strategy 2	4.432; 0.72%	34.196; -1.43%

3.2.5. Case 4

- **Description:** Adjust the signal timing of the multiple (1 corridor) specified intersections by increasing the maximum green time by 50% of all stages during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday. Resulting in 2.85% average volume decrease and 0.19% average speed increase.
- **Results:**

  See 25.

Table 25 Results Case 4

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)

Volume	Strategy 1	35.093; 9.62%	3113.806; 51.01%
	Strategy 2	33.817; 35.65%	2990.788; 127.37%
Speed	Strategy 1	6.389; 7.02%	79.389; 21.13%
	Strategy 2	4.597; 4.46%	42.026; 21.15%

3.2.6. Case 5

- **Description:** Adjust the signal timing of the multiple (2 corridors) specified intersections by increasing the maximum green time by 50% of all stages during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday. Resulting in 0.29% average volume increase and 0.26% average speed increase.
- **Results:**

  See 26.

Table 26 Results Case 5

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	33.789; 5.55%	2323.625; 12.69%
	Strategy 2	29.115; 16.79%	1693.518; 28.75%
Speed	Strategy 1	5.803; -2.81%	60.429; -7.80%
	Strategy 2	4.415; 0.32%	34.079; -1.76%

3.2.7. Case 6

- **Description:** Adjust the signal timing of multiple (2 corridors) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (9:00–10:00) of morning peak hour (8:00–10:00) on a workday. Resulting in 9.35% average volume decrease and 2.53% average speed decrease.
- **Results:**

  See 27.

Table 27 Results Case 6

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	42.782; 33.64%	4922.168; 138.72%
	Strategy 2	31.422; 26.04%	2691.376; 104.61%
Speed	Strategy 1	7.882; 32.01%	115.483; 76.20%
	Strategy 2	5.843; 32.78%	65.238; 88.06%

3.2.8. Case 7

- **Description:** Base network during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday.
- **Results:**

  See 28.

Table 28 Results Case 7

Traffic Condition	Strategy	Forecasting Results	
		Network MAE	Network MSE

Volume	Strategy 1	13.453	338.661
	Strategy 2	10.948	231.331
Speed	Strategy 1	6.369	92.556
	Strategy 2	5.118	61.452

3.2.9. Case 8

- **Description:** Adjust the signal timing of multiple (2 corridors) specified intersections by changing the signal timing from fully-actuated signal timing to fixed-time signal timing during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday. Resulting in 0.46% average volume decrease and 2.59% average speed decrease.
- **Results:**

  See 29.

Table 29 Results Case 8

Traffic Condition	**Strategy**	**Forecasting Results**	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	13.729; 2.05%	356.919; 5.39%
	Strategy 2	11.425; 4.36%	251.938; 8.91%
Speed	Strategy 1	7.393; 16.08%	110.533; 19.42%
	Strategy 2	5.963; 16.52%	75.267; 22.48%

3.2.10. Case 9

- **Description:** Adjust the signal timing of the multiple (2 corridors) specified intersections by increasing the maximum green time by 20% of all stages during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday. Resulting in 0.08% average volume increase and 0.28% average speed increase.
- **Results:**

  See 30.

Table 30 Results Case 9

Traffic Condition	**Strategy**	**Forecasting Results**	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	13.518; 0.48%	335.990; -0.79%
	Strategy 2	10.869; -0.72%	229.865; -0.63%
Speed	Strategy 1	6.611; 3.80%	95.353; 3.02%
	Strategy 2	5.291; 3.38%	62.038; 0.95%

3.2.11. Case 10

- **Description:** Adjust the signal timing of the multiple (2 corridors) specified intersections by increasing the maximum green time by 50% of all stages during the second hour (22:00–23:00) of non-peak hour (21:00–23:00) on a workday. Resulting in 0.04% average volume increase and 0.16% average speed increase.
- **Results:**

  See 31.

Table 31 Results Case 10

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	13.461; 0.06%	344.918; 1.85%
	Strategy 2	11.018; 0.64%	238.998; 3.31%
Speed	Strategy 1	6.466; 1.52%	95.460; 3.14%
	Strategy 2	5.081; -0.72%	60.562; -1.45%

3.2.12. Case 11

- **Description:** Increase the speed limit of the corridor with heavier flow to 80 km/h during the morning peak hour (8:00–10:00) on a workday. Resulting in 3.54% average volume increase and 6.94% average speed increase.
- **Results:**

  See 32.

Table 32 Results Case 11

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	29.272; -8.56%	1802.962; -12.56%
	Strategy 2	24.322; -2.43%	1229.494; -6.53%
Speed	Strategy 1	5.488; -8.09%	59.438; -9.31%
	Strategy 2	4.464; 1.43%	41.583; 19.87%

3.2.13. Case 12

- **Description:** Decrease the speed limit of the corridor with lighter flow to 40 km/h during the morning peak hour (8:00–10:00) on a workday. Resulting in 0.85% average volume decrease and 1.18% average speed decrease.
- **Results:**

  See 33.

Table 33 Results Case 12

Traffic Condition	Strategy	Forecasting Results	
		Network MAE (absolute; % change vs. base case)	Network MSE (absolute; % change vs. base case)
Volume	Strategy 1	30.908; -3.45%	2042.461; -0.94%
	Strategy 2	29.532; 18.47%	1960.214; 49.02%
Speed	Strategy 1	6.380; 6.87%	73.135; 11.59%
	Strategy 2	4.657; 5.83%	39.306; 13.31%

3.3. Discussion

A large number of findings and insights can be drawn from the results. This section is organised into two parts. First, we present the key findings from the scenario analysis, viewed from the digital twin perspective. Then, we discuss the insights gained from the evaluation of the AI model, based on the test cases.

3.3.1. Insights from digital twin scenario analysis

We first discuss findings and insights from digital twin scenario analysis. To enhance readability and presentation, the discussion is organized into batches of scenarios, with each batch comprising six scenarios.

3.3.1.1. Scenario 1-6

These six scenarios involve soft changes such as shifting from fully-actuated to fixed signal timing and implementing speed limit reductions during peak hour. The simulation period spans one hour, with all modifications implemented at the start of the simulation. Key findings and insights include:

- Changing signal timing from actuated to fixed-time signal control at different intersections can have significantly varying impacts on network performance (e.g., the effect on average speed in Scenario 1 is 858% of that in Scenario 3). Similarly, changing signal timing from actuated to fixed-time across different corridors (comprising multiple intersections) can result in different levels of impact on network performance (e.g., Scenarios 2, 4, and 5). This underscores the benefits of analysis using a digital twin.
- With the exception of Scenario 5, all cases where the signal timing is changed from actuated to fixed-time result in varying degrees of average speed reduction (with a maximum decrease of 8.15%). This demonstrates the effectiveness of actuated signal timing.
- The reason for Scenario 5's differing outcome (minimal impact on average speed) could be that it corresponds to a major corridor that is already near saturation during the morning peak, limiting the impact of signal optimization.
- Reducing the speed limit from 50 km/h to 20 km/h along the studied road section (Scenario 6) has a similarly significant effect on average speed as changing all intersection signals from actuated to fixed-time control (Scenario 2).

3.3.1.2. Scenario 7-12

These six scenarios focus on fully-actuated signal timing settings during the peak hour. The scenarios involve modifications to parameters such as maximum green time and gap time. The simulation period spans one hour, with all changes implemented at the beginning of the simulation. Key findings and insights include:

- Applying identical signal setting changes to different intersections produces varied outcomes, suggesting that a digital twin approach can optimize traffic signal management by tailoring adjustments to the unique characteristics of each intersection, rather than relying on a uniform strategy.
- For a specific intersection, adjusting the maximum green time in an actuated signal timing results in a speed reduction not exceeding 0.7% in either case (Scenario 7), while switching from actuated to fixed-timing control causes a 2.47% reduction (Scenario 1). This highlights the robustness of fully actuated systems, attributable to their adaptive mechanism that adjusts phases based on real-time traffic demand, outperforming the inflexibility of fixed-timing systems.
- The most significant impact on average speed arises from an excessively short gap time (1.5 seconds) at certain intersections (Scenario 8), indicating that too small a gap time should be particularly avoided, which can be due to potential reasons like disrupting traffic flow by trapping vehicles in the intersection and reducing overall throughput as queues build up from incomplete clearances.

- Fine-tuning signal settings—such as increasing maximum green time to a certain level and specifically for the busier direction—can dramatically improve average speed (e.g., a 450% increase in Scenario 11 compared to Scenario 9). This demonstrates that data-driven, targeted optimizations are far more effective than broad, across-the-board changes.

3.3.1.3. Scenario 13-18

These six scenarios focus on fully-actuated signal timing settings during the peak hour. The scenarios involve modifications to parameters such as maximum green time and gap time. Meanwhile, the simulation period extends to two hours, with signal timing changes implemented at the end of the first hour of the simulation. Key findings and insights include:

- For both directions of an intersection (Scenarios 13 and 15), a 50% change in maximum green time resulted in improved average vehicle speeds. This suggests that significant parameter adjustments may be necessary to achieve noticeable improvements in network performance, as smaller changes (e.g., 10% or 20%) did not yield similar benefits.
- Increasing the gap time for the busier direction of the intersection during peak hours (Scenario 14) had no impact on network performance. This is likely because the high traffic volume on these segments prevented vehicle headways from exceeding 3 seconds, rendering the gap time adjustment ineffective. Conversely, adjusting the gap time by as little as 0.5 seconds for the less busy direction (Scenario 16) led to a speed reduction of 0.8% in that direction. These findings highlight the importance of tailoring fully-actuated signal parameter adjustments to the actual traffic conditions (e.g., traffic volume) of each segment.
- Except for Scenario 14, all other scenarios resulted in increased average speeds through parameter tuning, demonstrating the effectiveness of the adopted strategies, including:
  - Increasing maximum green time for the busier direction of an intersection (Scenario 13).
  - Reducing maximum green time for the less busy direction of an intersection (Scenario 15).
  - Reducing gap time for the less busy direction of an intersection (Scenario 16).
  - Increasing maximum green time for the major corridor in a network (Scenarios 17 and 18).

3.3.1.4. Scenario 19-24

These six scenarios involve changes to signal timing configurations, including adjustments to fully-actuated signal timing settings, transitions from fully-actuated to fixed signal timing, and modifications to fixed signal timing during the peak hour. The simulation period spans two hours, with signal timing changes implemented at the end of the first hour. Key findings and insights include:

- Extending the maximum green time to an additional major corridor (Scenario 19) results in a 36.84% greater improvement in average vehicle speed compared to extending it on a single corridor (Scenario 18). This finding emphasizes the importance of optimizing signal timing across a broader network, rather than focusing on isolated segments, and underscores the value of large-scale digital twins that enable evaluation and refinement across extensive urban areas.
- When two corridors are switched from actuated to fixed-time signal timing (Scenario 24), the reduction in average vehicle speed is 1.85 times greater than when only one corridor is changed (Scenario 22) and 2.41 times greater than when only one intersection is altered (Scenario 20). This indicates that as more intersections transition from actuated to fixed-time signal timing, the negative impact on network performance intensifies.
- The negative impact of switching from fully-actuated to fixed-time signal timing can be reduced by optimizing the signal timing, specifically by increasing the green time for the stage with higher traffic volume. This fine-tuning of fixed-time signal settings proves effective, resulting in a 49.52% relative reduction in the decrease of average vehicle speeds for one

intersection and a 57.66% reduction for one corridor, compared to unoptimized fixed-time signal timing. This demonstrates the value of targeted adjustments in improving network performance under fixed-time control.

3.3.1.5. Scenario 25-30

These six scenarios involve changes to fully-actuated signal timing settings and shifts from fully-actuated to fixed signal timing during the non-peak hour. The simulation period spans two hours, with signal timing changes implemented at the end of the first hour. Key findings and insights include:

- Unlike the peak hour scenarios (13 and 17), adjusting the maximum green time—whether for the busier direction of a single intersection or the major corridor it belongs to (Scenario 25)—had no effect on network performance, which is likely because the low traffic volumes during non-peak hours don't reach the existing high maximum green time limits. This shows how a digital twin model can pinpoint ineffective traffic control measures.
- Increasing the maximum green time for the two major corridors in the network (Scenario 26) improved performance. This adjustment proved effective in both peak (Scenario 19) and non-peak hours.
- In contrast to peak hour results (Scenario 14), increasing the gap time for the busier direction of the intersection (Scenario 27) enhanced performance. However, reducing the gap time for the less busy direction (Scenario 28) didn't improve performance, unlike in peak hours (Scenario 14). This indicates that signal timing adjustments need to account for differing traffic patterns between peak and non-peak periods.
- Increasing the gap time for the busier direction at more intersections along a major corridor (Scenario 29) didn't lead to further performance gains. This suggests that the benefits of such changes may not increase proportionally with the number of adjusted intersections.
- Switching from fully-actuated to fixed-time signal timing for two corridors (Scenario 30) significantly worsened network performance. This negative impact, also seen in peak hours (Scenario 24), highlights the value of adaptive signal systems, even in lighter traffic conditions.

3.3.1.6. Scenario 31-36

These six scenarios involve speed limit changes during both peak and non-peak hour. The simulation period spans two hours, with speed limit changes introduced at the start of each simulation. Key findings and insights include:

- Compared to a corridor with lighter flow (Scenario 32), raising the speed limit to 80 km/h during the peak hour in the corridor with heavier flow (Scenario 31) led to a more substantial improvement in network performance. This indicates that increasing speed limits may be more effective in managing higher traffic volumes. However, this approach carries potential drawbacks, such as heightened safety risks due to faster speeds during congested peak periods, which could increase the likelihood of accidents.
- Lowering the speed limit to 40 km/h in the corridor with heavier flow during the morning peak hour (Scenario 33) also enhanced network performance. In contrast, this improvement was not observed during non-peak hours (Scenario 34) or in the corridor with lighter flow (Scenario 35). This effect is likely due to the reduced speed mitigating downstream congestion by regulating traffic flow and preventing bottlenecks during peak times.
- Reducing the speed limit to 40 km/h in the corridor with lighter flow during peak hours (Scenario 35) resulted in a markedly greater decline in network performance compared to non-peak hours (Scenario 36), with volume and speed dropping by 672.73% and 107.02% more, respectively. This implies that such adjustments, potentially triggered by specific events, should ideally be applied during non-peak hours to lessen their negative impact on the network.

- Adjusting speed limits had a more pronounced effect on network performance than modifying signal control. This suggests that speed limit changes could serve as a potent tool for traffic management.

3.3.2. Insights from AI model evaluation

This section discusses findings and insights from AI model evaluation.

We first analyse the base case results for peak-hour forecasting. From Table 21 it can be observed that, compared to Strategy 1, Strategy 2 lead to an improvement of 22.12% in MAE for volume forecasting, and 26.30% in MAE for speed forecasting. These reductions are substantial, indicating that Strategy 2 captures traffic dynamics more effectively. Moreover, the slightly larger improvement in speed forecasting (26.30% vs. 22.12%) suggests that Strategy 2's use of future data may be particularly effective for predicting traffic speed, which is often more prone to variation and exhibits greater dynamism. In addition, it is also worth noting that Strategy 2's reliance on future data introduces a dependency that may not always be met. Strategy 1, while less accurate, is more robust due to its independence form real-time data.

It is also worth note that the AI model demonstrates efficient inference capability, with each sample prediction taking approximately 70 microseconds. This enables rapid assessment of traffic conditions under diverse control strategies without requiring model fine-tuning for each scenario. Such speed and flexibility make the model highly suitable for integration into real-time decision-support systems, offering timely insights that can enhance the responsiveness and effectiveness of traffic management strategies.

12 cases are subsequently discussed. To enhance readability and clarity, the discussion is organized into three batches of four test cases each.

3.3.2.1. Case 1-4

- Across all test cases, Strategy 2 outperformed Strategy 1, indicating that Strategy 2 is a more effective method. However, it requires high-quality and readily available real-time traffic data, which may pose implementation challenges.
- The most significant changes occur for volume in Case 4 and speed in Case 1. In these cases, Strategy 2 yields lower MAE and MSE values compared to Strategy 1, indicating higher overall accuracy. However, its percentage change relative to the base case is substantially higher. This suggests that while Strategy 2 is more accurate under typical conditions, it is also more sensitive to significant traffic state changes (which are often associated with large deviations from normal traffic patterns).
- In scenarios with relatively minor changes in traffic conditions (e.g., speed in Cases 2, 3, and 4), Strategy 2 exhibits a smaller decline in forecasting accuracy. This may be because its mechanism can effectively adapt to small changes and is well-suited to handling situations where traffic conditions are stable or exhibit only minor variations.
- Compared to Case 1, Cases 2 and 3 involve greater adjustments to signal timing but result in smaller changes in traffic conditions. However, the AI model in Case 1 exhibits a larger deviation in performance from the baseline than in Cases 2 and 3. This suggests that the model's performance is more strongly influenced by the actual traffic state than by the magnitude of signal timing adjustments. In other words, larger changes to signal timing do not necessarily lead to proportionally greater degradation in AI model performance.

3.3.2.2. Case 5-8

- Compared to Case 4, Case 5 involves more significant changes to the network and a larger increase in average speed. However, its impact on speed forecasting is lower than that of Case 4. This suggests that, despite extensive signal adjustments, the overall traffic dynamics may not be strongly affected. It also indicates that traffic signal changes alone may have limited impact, especially when not aligned with underlying demand patterns or network bottlenecks.

- Case 7 serves as the base case for the non-peak hour. Compared to the base case for the peak hour, Case 7 has lower volume forecasting error and higher speed forecasting error. Given that non-peak periods generally have lower traffic volumes and higher speeds, this suggests that conditions with lower volume or speed may be linked to lower MAE/MSE values. This is likely due to the characteristics of these two metrics, which are sensitive to the magnitude of the underlying values.
- The most significant changes in both average volume and speed occur in Case 6, which also leads to the largest errors, suggesting that the forecasting model's performance is limited in this scenario (i.e., the transition to fixed signal timing across a wide area). Moreover, Strategy 2 yields lower MAE and MSE values than Strategy 1, indicating its superiority persists under this condition.
- In Case 6, the average volume increases by 228% compared to Case 4. Nevertheless, the volume forecasting performance under Strategy 2 remains the same level, highlighting the robustness and effectiveness of this adaptive strategy.
- Compared to Case 6, Case 8 applies the same signal timing adjustment but during peak hours. Despite identical interventions, Case 6 shows a greater decline in forecasting accuracy, indicating that the impact of signal timing on forecasting performance is amplified under congestion. This also suggests that the AI model appears to be more sensitive to traffic demand levels than to the magnitude of the network adjustment.

3.3.2.3. Case 9-12

- Comparing Case 5 and Case 10, with the same change implemented to the network, applying it during non-peak hours causes less impact on the AI model's forecasting performance during peak hours, compared to their respective base cases. This again shows that forecasting performance is more affected under higher traffic demand.
- Across Cases 7, 8, 9, and 10 (all non-peak-hour scenarios), Strategy 2 consistently outperforms Strategy 1, regardless of whether the network change involves switching from fully-actuated to fixed-time signal control or simply extending the maximum green time. Likewise, in Cases 11 and 12 where the only change is a reduction or increase in speed limit, Strategy 2 still maintains its advantage over Strategy 1. Together, these results suggest a broadly superior robustness of Strategy 2 under varied network interventions.
- Case 5 and Case 9 both feature similar average speed changes, yet they diverge in forecasting accuracy: in Case 5, the model's speed forecasts are generally more accurate than the peak-hour baseline, whereas in Case 9, forecasts degrade compared to its non-peak baseline. This discrepancy highlights that identical network changes can have opposing impacts on forecasting error, depending critically on the underlying traffic conditions.
- Comparing Cases 9 and 10, where increasingly significant changes were applied to the signal plan, the difference in forecasting performance does not necessarily increase. This suggests that under relatively low demand, more aggressive network adjustments do not necessarily lead to larger changes in forecasting performance.
- With a noticeable volume increase in Case 11, the performance of both strategies improves, indicating that volume increase to a certain extent can enhance AI forecasting model performance. In general, when demand is fixed (e.g., peak hour or non-peak hour) and changes are made to the network, the AI forecasting model tends to perform better with increased volume and speed rather than decreased volume and speed (e.g., comparing Case 11 and Case 12).

4. Conclusion

This section presents the evaluation of a virtual AI-driven Traffic Management Centre (TMC), conducted using the developed digital twin and AI forecasting model. A total of 36 scenarios were designed and implemented in VISSIM, covering a comprehensive range of TMC control strategies. The performance of the AI model in forecasting traffic states was evaluated by comparing its predictions with VISSIM simulation outputs, which served as the ground truth. Two distinct forecasting strategies were employed, and their effectiveness was analysed across 12 test cases.

A wide array of findings emerged from the analysis, leading to several key insights, such as the importance of tailoring control strategies to specific network segments and time periods, the benefits of implementing Adaptive Signal Timing, and the value of large-scale digital twins in supporting data-driven traffic management decisions. From the AI forecasting model perspective, the results underscore Strategy 2’s robustness and adaptability across varied scenarios. Moreover, forecasting accuracy appears to be more strongly influenced by underlying traffic conditions than by network interventions alone. It is also worth noting that the AI model demonstrates efficient inference, with each prediction taking about 70 microseconds, which makes it well-suited for real-time decision support, enabling timely and effective traffic management.