Traffic Intersection Optimization Based on Random Forest and SUMO Simulation in Xi'an

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Abstract: With the rapid pace of urbanization, traffic congestion, especially at intersections, has become a significant challenge in cities like Xi'an, China. This study conducted a comprehensive analysis of traffic congestion issues, with a specific focus on the intersection of Shang Hong Road and Shang Ji Road, a critical bottleneck area in Xi'an City. Utilizing AutoCAD for road layout optimization design, the paper simulated the optimized solution using the SUMO simulation tool. Furthermore, a random forest model was employed to predict traffic flow, leading to recommendations for optimizing signal light duration and lane configuration. The research findings indicate that an enhanced traffic network design and signal light configuration can significantly improve intersection throughput, reduce delay times, and enhance traffic safety. This study provides scientifically grounded optimization suggestions for urban traffic management authorities, offering practical measures to improve traffic efficiency, alleviate congestion, and contribute to safer and more sustainable urban environments.

1 INTRODUCTION

With the acceleration of urbanization, the problem of traffic pressure has gained increasing attention from the public, especially in traffic intersections where heavy congestions seriously hinder the smooth flow of commuting vehicles (Afrin and Yodo, 2020). For example, in many cities in China, due to heavy traffic and unreasonable road design, intersections have been held up for a long time, causing great inconvenience to citizens' daily lives. These congestions influence the travel safety and commute efficiency of citizens. Moreover, extended periods of stagnation and low speed of vehicles lead to more greenhouse gas emissions, resulting in environmental pollution. Therefore, it is of immense importance to improve the overall performance of the existing urban transportation system and the layout of the road networks to alleviate the congestion at intersections effectively.

However, the current traffic junction design is inefficient for signal control and timing, and lane settings have improper situations. For example, the traffic signal timing scheme fails to fully consider the dynamic change of traffic flow, resulting in the traffic flow in peak hours not being effectively channelling. The lane turning setting is not reasonable, the number of lanes does not match the traffic flow, causing some lanes in a saturated state for a long time. These urgently need scientific analysis and optimization to improve their operational effectiveness. In this context, big data applications and intelligent transportation systems are increasingly required to provide data-driven solutions to optimize traffic routes, traffic distribution, and general management. (Brown et al., 2022). These integrations increase the responsiveness and flexibility of urban transport systems to reduce congestion and improve safety and environmental quality (Haydari and Yilmaz, 2022).

The application of intelligent transportation systems (ITS) and big data algorithms in urban traffic management is getting more attention from academia and industry. They can provide a scientific basis for transportation management and optimization based on real-time traffic flow monitoring and massive data analysis (Cheng, Pang and Pavlou, 2020) According to the research, scholars have proposed various methods to improve the current traffic congestion in intersections. For example, refining the timing of

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signal lights, and upgrading lane Settings, could alleviate traffic congestion, improve traffic efficiency, and reduce environmental pollution. Eom and Kim (2020) argue that a reasonable timing schedule for signal lights can significantly improve the capacity and safety of the roads. Zhao et al. (2013) suggest that meticulously designed lane turn signs can ensure that vehicles enter and exit smoothly without causing severe traffic congestion. In addition, simulation technologies such as Simulation of Urban Mobility (SUMO) are becoming widely used in traffic management and optimization. The results of these simulations can work as vital support for renovating the intersection lane layout (Shirazi, Morris and Zhang, 2023). Through these analyses, the effect of distinctive design plans can be evaluated to provide a scientific basis for perfecting traffic intersections

To solve the traffic problem and the inefficiency of the intersection, this paper carries out research experiments to study the design problems in the design of traffic intersections on Shang Hong Road and Shang Ji Road in Xi'an City and proposes improvements based on calculation and analysis. The article will achieve the research goals based on the following steps: Firstly, it will collect and analyze the traffic flow during morning and evening and flat peaks. Additionally, the paper will redesign the junction using CAD software. Moreover, it will use SUMO simulation software to simulate and analyze the improved design and propose optimized signal timing schemes and lane design suggestions based on the simulation results. This study is expected to provide scientific suggestions for urban traffic management departments to improve the operation efficiency and safety of traffic intersections.

2 RESEARCH AREA AND METHODOLOGY

2.1 Overview of the Targeted Area

2.1.1 Introduction of the Intersection

With the progress of urbanization, the traffic pressure of Xi 'an is increasing daily, and the traffic congestion problem has become one of the bottlenecks restricting the city's further development. Especially in some important traffic nodes and economic development areas, the traffic flow is dense, and the congestion is serious. Therefore, it is of great practical significance to solve the traffic problems in these areas. Shang Hong Cross Road is a typical bottleneck area, located at the intersection of Xi 'an Economic Avenue and Shang Ji Road Science and Technology Development Zone. The north-south main Road Shang Hong Road and the National Highway 1310 Express Road (known as Shang Ji Road) form this junction. The intersection is located in a complex area of infrastructure, the northern area is mostly residential areas, and the south, east, and west are distributed with several types of factories and commercial areas. This diverse regional functional layout brings a lot of commuting and coordination traffic needs. In addition, there are many important traffic attractions near the intersection, such as Xi 'an Economic Development Zone No. 8 Primary School, Yurun Market, and Master Kong Storage and Transportation Center, which further aggravate the traffic flow and congestion at the interchange. Therefore, it is of great significance to study and optimize the traffic organization and management of Shang Hong Cross Road to improve the traffic situation in this area (Figure 1).

Figure1: Actual map of the intersection (Photo/Picture credit : Original).

2.1.2 Current Problems

The convergence of these major roads at the intersection leads to an increasing flow of vehicles, exacerbating the traffic congestion risk. Traffic congestion is particularly severe during peak hours, causing significant delays and increasing the risk of accidents. The presence of important educational and commercial establishments further increases the traffic volume, with parents picking up students and commercial vehicles moving in and out of storage facilities, compounding the traffic problem. The existing road infrastructure cannot accommodate such a high volume of traffic, resulting in a bottleneck phenomenon that affects not only the traffic in the area but also the overall traffic flow in the technical development zone. To address this issue, comprehensive traffic management strategies and infrastructure improvements are required to ease congestion and ensure smoother traffic flow.

2.1.3 Data Collection

Through field measurement and mechanical counting method, the study obtained the following traffic flow of left-right turning and going straight through the intersection within one hour of the morning and evening peak. Through the vehicle conversion coefficient table in Table 1,

Table 1: Vehicle conversion factor.

Vehicle Type	Vehicle Conversion Factor	Description
Small Vehicle	1.0	Passenger vehicles with ≤19 seats and cargo vehicles with ≤2t load capacity.
Medium Vehicle	1.5	Passenger vehicles with >19 seats and cargo vehicles with >2t to ≤7t load capacity.
Large Vehicle	2.0	Cargo vehicles with >7t to ≤14t load capacity.
Trailer	3.0	Cargo vehicles with >7t to ≤14t load capacity.

2.2 Methodology

AutoCAD software is produced by the United States Autodesk Co., LTD. (Autodesk), which is an automatic computer-aided design software, that can be used to draw two-dimensional drawings and basic three-dimensional designs, it does not need to know programming, you can automatically draw, so it is widely used in the world, can be used in civil construction, decoration, industrial drawing, engineering drawing, engineering drawing, electronics industry, clothing processing, and other fields. CAD tools can be used to design and optimize road layouts, ensuring proper allocation of lanes for vehicles, pedestrians, and cyclists to reduce traffic congestion (Omura and Benton, 2019).

SUMO is an open-source traffic simulation software that can simulate and analyze urban traffic flow. Using SUMO, city planners can predict the impact of different planning options and determine the most efficient transportation solutions. Moreover, with SUMO, it is possible to simulate urban traffic conditions under different traffic flows and evaluate the feasibility of different traffic plans. In addition, traffic signal Settings can be optimized through simulation to reduce vehicle waiting times and improve overall traffic efficiency. This integrated approach enables a comprehensive assessment and improvement of urban traffic management strategies, contributing to a more effective and efficient urban traffic flow (Krajzewicz, 2010).

2.3 Traffic Flow Prediction Using Random Forest Model

This paper will apply the Random Forest Model to experiment with traffic flow prediction. Random Forest is a supervised data mining algorithm. It is a classifier model composed of multiple CART decision trees. The resulting decision trees form a random forest model (Liu and Wu, 2017).

The Random Forest model's prediction formula can be succinctly expressed as:

$$\hat{Y}=\frac{1}{N}\sum_{i=1}^{N} f_i(X) \tag{1}$$

where $(\hat{Y})$ represents the estimated total traffic volume, (N) denotes the number of decision trees, $(f_i(X))$ corresponds to the prediction outcome of the $(i)-th$ decision tree, and (X) encapsulates the input feature vector, including the time (in hours and minutes). This ensemble method aggregates the predictions from individual decision trees, effectively capturing complex relationships within the data, leading to more robust and accurate traffic volume forecasts.

In this case, the formula of the Random Forest Model can be used as:

$$\widehat{Y_t} = \frac{1}{100}\sum_{i=1}^{100} f_i(\mathrm{Hour}_t, \mathrm{Minute}_t) \tag{2}$$

Where $(\widehat{Y_t})$ represents the estimated total traffic volume at the time (t), (N) denotes the number of decision trees (set to 100 in this example), $(f_i(\mathrm{Hour}_t, \mathrm{Minute}_t))$ corresponds to the prediction outcome of the $(i)-\mathrm{th}$ decision tree based on the hour and minute at time (t), and (X) encapsulates the input feature vector, including the time (in hours and minutes). This ensemble method aggregates the predictions from individual decision trees, effectively capturing complex relationships within the data, leading to more robust and accurate traffic volume forecasts.

3 RESULT ANALYSIS

3.1 Using CAD to Upgrade the Intersection Network

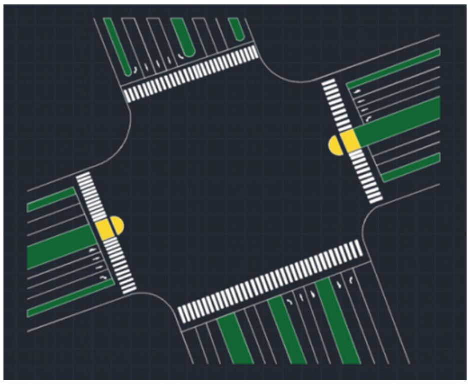

Figure 2: CAD drawing of the original intersection (Photo/Picture credit : Original).

Figure 2 shows the existing road network structure, the setting of turning lanes is not reasonable. Due to the insufficient width of the lane or the unreasonable setting of the signal light, vehicles interfere with each other when turning, which is easy to cause a collision, thus obstructing the smooth passage of traffic at the intersection. Secondly, the setting of the safety islands is not perfect, only the east and west safety islands are set up. The north-south road surface is wider, but there is no safety island, so it causes a safety risk for pedestrians crossing the street. In addition, the intersection does not effectively mark the specific location of the non-motorized lane, resulting in the phenomenon of grabbing the lane between non-motor vehicles and motor vehicles, which not only causes congestion but also causes security risks.

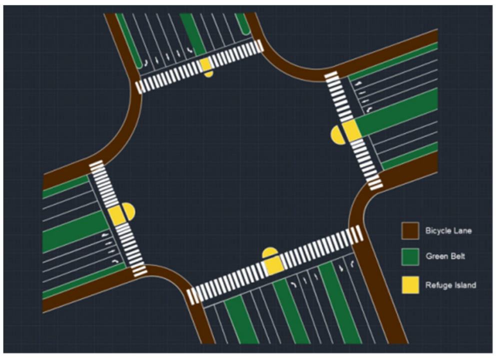

Figure 3: CAD drawing of the improved intersection (Photo/Picture credit : Original).

The upgrade plan for the network is shown in Figure 3. In the figure, this research changed the steering of the north-to-south lanes and concentrated the right-turn lanes on the right side of the road. This way, there will be no congestion and traffic standstill caused by straight-going vehicles and right-turning vehicles competing under the same green light. Secondly, considering the width of the intersection and the possibility of pedestrians crossing the street twice, this paper added two safety islands at the east-west zebra crossing. According to the standard, the width of the safety island is at least 1.5 meters, and if it needs to accommodate wheelchairs, etc., the width needs to be set to 2 meters. At the same time, the safety island design used in the paper will have sections at both ends that are raised above the ground to enhance the safety of pedestrians and prevent vehicle strikes. At the same time, the middle part of the safety island is level with the ground, which is convenient for the elderly and disabled people to use. In addition, the middle part of the safety island is coated with anti-slip lines to prevent slipping in rain and snow and improve visibility, and its two ends are also coated with yellow reflective material, which is easier to see at night (Li, Yang and Yin, 2010). Finally, this research set up a non-motorized lane, as shown in the brown area in the figure, which separates the non-motorized traffic flow from the motorized traffic flow, improving the efficiency and safety of the intersection

3.2 Prediction Result Analysis

3.2.1 Morning Peak Analysis

As shown in Figure 4, during the morning peak, the traffic flow prediction indicates that in the coming hour, there will be an increasing number of vehicles passing through the intersection, especially between 8:45 and 9:20. Traffic started at 8:45 am with 169 vehicles, then steadily increased to 194 vehicles at 8:55 am and reached its peak at 9:20 am with 209 vehicles. Subsequently, traffic decreased slightly to 164 vehicles at 9:30 a.m. and 152 vehicles at 9:40 a.m. This trend indicates that traffic congestion will gradually increase during peak hours in the morning, especially around 9:20 am, when traffic may reach saturation. Therefore, to reduce traffic congestion around 9:20, it is suggested that the design of traffic lights be adjusted, traffic flow should be restricted during rush hour, and management of the surrounding area should be optimized.

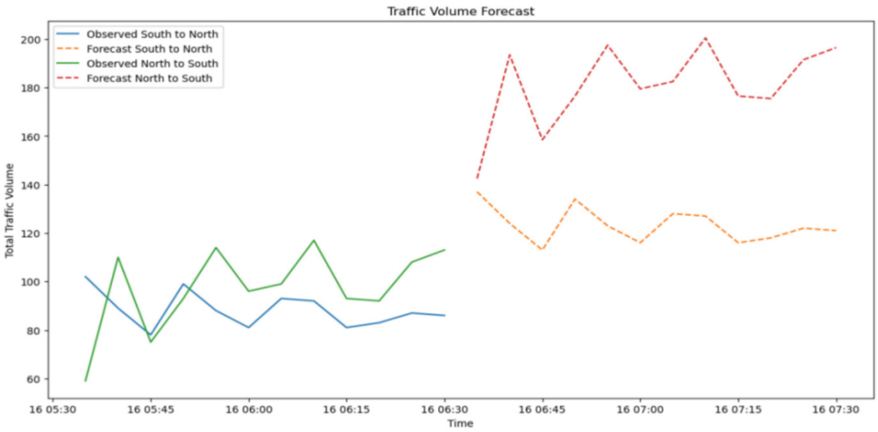

Figure 4: Traffic volume forecast in the morning peak (Photo/Picture credit: Original).

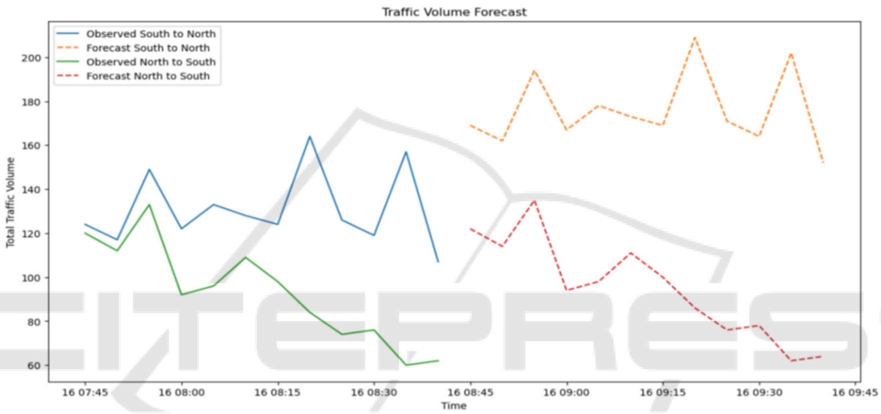

Figure 5: Traffic volume forecast in the evening peak (Photo/Picture credit: Original).

For traffic from north to south, as forecast, morning peak traffic is steady but tends to decrease. From 8:45 to 12:22, it gradually decreases until 9:40 to 64h. The traffic volume in this direction is small and will decrease gradually. However, attention must be paid to traffic management to prevent unforeseen events from causing disruptions. For example, early morning traffic management should be improved, sufficient labor and equipment should be provided, and accidents or technical failures should be recorded promptly to reduce the risk of traffic accidents.

3.2.2 Evening Peak Analysis

During evening peak periods, north-south traffic shows significant variations, especially from north to south. Concrete data in Figure 5 show that north-south traffic increased from 142 at 6:35 to 193 at 6:40, with a peak of 200 at 7:10. Traffic subsequently fluctuated between 175 and 200 vehicles and continued until 7:30. Traffic from the south to the north, on the other hand, is relatively stable and is expected to fluctuate between 113 and 137 vehicles between 6:35 and 7:30.

This forecast indicates that the north-to-south tracks could face significant congestion, especially during the evening rush hour at approximately 7:10. In addition, large gaps between north and south can lead to bottlenecks at intersections, further exacerbating congestion. It is therefore recommended that the operating time of the traffic lights be dynamically adjusted during the evening rush hour to give priority to north-south traffic. At the same time, consideration could be given to creating additional temporary lanes in the north and south directions to optimize the use of the lanes and allow rush-hour vehicles to move quickly in the priority sections.

When the morning and evening peak traffic forecasts are considered, traffic varies between periods and directions. During the morning peak, traffic reaches its highest at 9:20 (209 vehicles) before tapering off from north to south to the lowest (64 vehicles). During the evening peak, the traffic from north to south fluctuates widely, up to 200 vehicles, while the flow from south to north is more stable.

These data show that some important sections present a clear risk of congestion during peak hours and require appropriate management measures.

To effectively address these challenges, improve real-time traffic monitoring and use intelligent transport systems (its) to dynamically adjust signaling periods and conduct traffic strikes by adding temporary lanes and optimizing lane use. Tempering returns should be considered. In addition, continuous data analysis and forecasting will provide an important reference for future traffic management and will help to develop more scientific traffic channeling scenarios and improve the overall efficiency of traffic exploitation.

3.3 SUMO Simulation Analysis

3.3.1 Network Structure and Signal Optimization

The diagram below shows the typical design of a four-lane crossing in SUMO. To manage the volume of traffic in the north-south direction, the emphasis is on improving the tracks in the north-south direction. The design uses a crossing plan to handle north-south traffic. The track configuration in all directions includes a left, right, and right turn. The tracks intersect in the central section of the crossing, allowing safe and smooth movement of vehicles in all directions. At the same time, detectors are installed at each entrance. These detectors can monitor traffic in real-time in all directions and provide data to dynamically adjust signal synchronization. Crossings are designed to maximize vehicle traffic efficiency and reduce potential collisions and congestion.

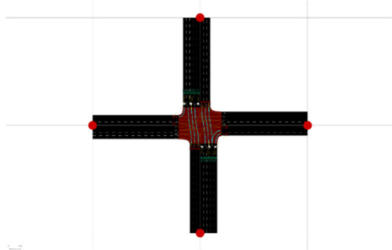

Figure 6: Road structure image after improving the lane network using SUMO (Photo/Picture credit : Original).

The diagram below shows the optimal signal time at this crossing. Based on traffic data provided by the SUMO simulation tool, the green light time is dynamically adjusted according to traffic to reduce vehicle delays and improve the effectiveness of bans. Especially in directions where there is significant traffic in the north-south direction, the duration of the green light was extended, allowing vehicles from that direction to cross the crossing quickly, reducing waiting times and potential congestion. As shown in the chart, from north to south, the green light is 20 seconds long, the red light is 63 seconds long, and the yellow light is fixed for 3 seconds in a signal period. At the same time, the green light is 40 seconds long and the red light is 25 seconds long in a signal period from south to north.

With the improved traffic light configuration, it is possible to effectively avoid the north-south and east-west traffic lights at the same time and reduce traffic congestion. This time allocation, which allows vehicles to travel in one direction at all times, reduces the risk of accidents and improves crossing safety. A reasonable allocation of time can improve crossing

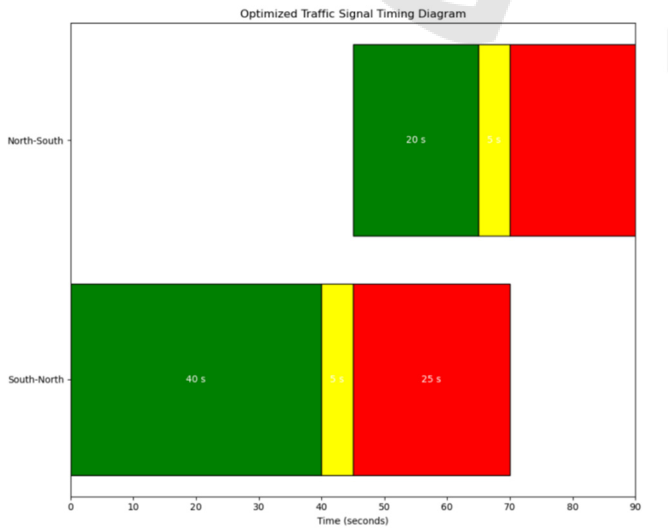

Figure 7: Signal light timing improvement diagram (Photo/Picture credit: Original).

capacity. By analyzing traffic in different directions, this program defines a reasonable green light time based on actual traffic, which ensures the efficient passage of traffic. Also, switch traffic lights regularly every week to make traffic flow smoother. The optimized signal configuration scheme ensures the stability of the road sign system in the actual operation by clearly setting the green, yellow, and red times. This stable signal switching reduces driver uncertainty and improves road traffic reliability.

3.3.2 Simulation Results Comparison

This study analyses in detail traffic performance indicators before and after upgrading the crossing network and traffic light optimization using SUMO simulation data. The indicators analyzed are the Average Travel Time, the Average Speed, the Average Time Lost, the Average Time Lost Within, and the Average Duration Within. The following is a summary of the results of the analysis.

As shown in Tables 6 and 7, the average left-hand car travel time increased from 47.97 seconds to 43.32 seconds, an improvement of approximately 9.7%. The average driving time of direct line vehicles decreased by 21.7% from 21.84 seconds to 17.15 seconds. The average driving time of vehicles turning to the right decreased from 17.91 seconds to 14.05 seconds, an improvement of 21.5%. The bar chart in Figure 8 demonstrates directly that these reductions show that optimization measures have significantly improved driving efficiency in all directions.

As shown in Figure 8, the average speed in all directions was increased by optimization. Tables 6 and 7 indicates that the average speed of the left cars increased by 42.0% from 2.76km /h to 3.92km /h. The average speed of straight-line vehicles increased by 14.8% from 6.16 km/h to 7.07 km/h. The average speed of right turns increased from 4.23 km/h to 4.42 km/h, an increase of 4.5%. The increase in average speed means smoother traffic and less congestion.

Table 2 and Table 3 show that the average lost time is an important measure of the total number of vehicles delayed at crossings. Optimized traffic decreases in all directions. The average time lost by a left-hand vehicle decreased from 44.00 seconds to 37.23 seconds, a reduction of 15.4%. The average time lost for direct line vehicles decreased by 11.8% from 17.76 seconds to 15.67 seconds. The average time lost to a right turn decreased from 15.61 seconds to 10.01 seconds, a reduction of 35.7%. These results show that optimization significantly reduces delay time in all directions.

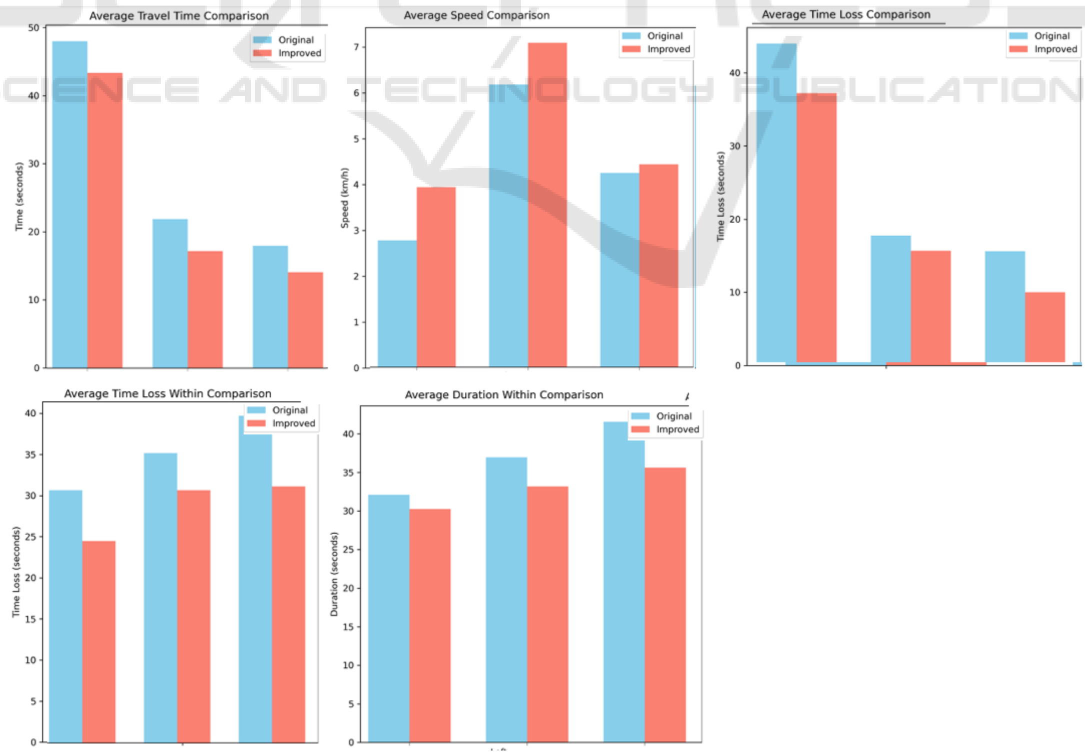

Figure 8: Comparison of different indicators before and after optimization (Photo/Picture credit: Original).

Table 2: Simulation results of different indexes before optimization.

Original	Average Travel Time	Average Speed	Average Time Lost	Average Time Lost Within	Average Duration Within
Left	47.97	2.76	44.00	30.47	32.10
Straight	21.84	6.16	17.76	34.93	36.95
Right	17.91	4.23	15.61	39.43	41.56

Table 3: Simulation results of different indexes after optimization.

Improved	Average Travel Time	Average Speed	Average Time Lost	Average Time Lost Within	Average Duration Within
Left	43.32	3.92	37.23	24.34	30.26
Straight	17.15	7.07	15.67	30.45	33.18
Right	14.05	4.42	10.01	30.92	35.62

The average time lost within the crossing has also been improved as shown in Figure 8. The average internal time lost by left-hand cars decreased from 30.47 seconds to 24.34 seconds, a reduction of 20.2%. The average loss of internal time for cars in direct service was reduced from 34.93 seconds to 30.45 seconds, a reduction of 12.7%. The average loss of internal time for cars that made a right turn was reduced from 39.43 seconds to 30.92 seconds, a decrease of 21.6% as shown in Tables 6 and 7. It reduces the stay time of vehicles inside the intersection and improves the efficiency of the passage.

The average crossing time has also been improved through optimization. The average length of a left turn decreased by 5.7% from 32.10 seconds to 30.26 seconds. The average duration of direct line vehicles decreased by 10.3% from 36.95 seconds to 33.18 seconds. Average right-hand vehicle travel time decreased from 41.56 seconds to 35.62 seconds, a reduction of 14.2% as shown in Tables 6 and 7. These improvements have significantly reduced the average stopping time of vehicles at crossings.

Overall, improvements to the crossing system and optimization of signal lights have significantly improved traffic efficiency. It reduces the time and waste of time on the road and also increases the average speed of vehicles, as demonstrated in Figure 9, after optimization, the number of vehicles queuing in the lane is significantly reduced. These improvements will improve traffic flow and reduce congestion, making an important contribution to urban traffic management.

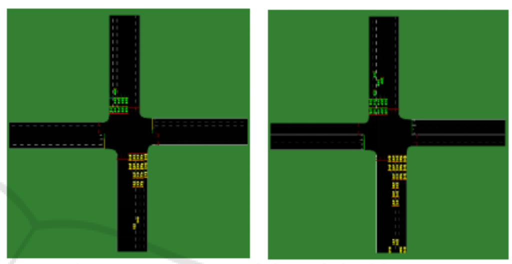

Figure 9: Comparison of the original lane queue (Left) with the improved lane queue (Right) (Photo/Picture credit : Original).

4 CONCLUSION

This research focused on a comprehensive analysis and design optimization to address traffic congestion at the intersection of Shang Hong Road and Shang Ji Road in Xi'an City. The project involved enhancing the road network layout through AutoCAD software and simulating the proposed improvements using the SUMO simulation tool. Additionally, a random forest model was utilized to forecast traffic flow, leading to recommendations for optimizing signal light durations and lane arrangements.

The findings indicate that the revised traffic network design and signal configurations can enhance the intersection's capacity, minimize vehicle delay times, and boost overall traffic safety. Specifically, The average travel time of left-turning, right-turning, and straight-moving vehicles experienced a significant reduction, resulting in improvements of 9.7%, 21.7%, and 21.5% respectively. Furthermore, there was a notable increase in average travel speeds: left-turning vehicles improved from 2.76 km/h to 3.92 km/h; straight-moving vehicles increased from 6.16 km/h to 7.07 km/h; and right-turning vehicles rose slightly from 4.23 km/h to 4.42 km/h—all indicating that optimized designs effectively reduce delays while enhancing vehicle throughput efficiency.

Looking into the future, it is recommended that real-time monitoring systems be further integrated with adjustments made to signal lights and lane configurations in response to evolving traffic patterns over time. In the future, consider introducing deep learning models, such as long short-term memory networks (LSTMs), to capture time-dependent relationships in traffic flow. Reinforcement learning algorithms can also be used to optimize signal timing dynamically and adjust based on real-time data. They could provide dynamic solutions for urban transportation systems while promoting smoother flows and environmental sustainability within city traffic networks.

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