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Application of the AI traffic signal control system to traffic carbon reduction: A case study of Xiangyang

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Abstract. To address the challenges of high carbon emissions in the transportation sector and the pronounced limitations of traditional traffic signal control systems, this study introduces a third-generation traffic control system—the Artificial Intelligence Traffic Signal Control System (AI-TSCS). Taking the Xiangyang National Vehicles-to-Everything (V2X) Pilot Zone Project as a case study, this study investigates its practical value in improving traffic efficiency and reducing carbon emissions. The study uses the emission-factor method to construct carbon accounting models for intersections and road segments, then compares traffic efficiency and carbon emissions before and after the project. Results show that, after the project, acceleration/deceleration time at intersections decreased by 15.9%, stopping time at intersections decreased by 17.6%, and the average speed on road segments increased by 15.2%. The project achieved an annual carbon reduction of 218,886.1 tCO_2, with a carbon reduction rate of 8.3%. These findings confirms that the AI-TSCS has significant effects on improving traffic efficiency and reducing carbon emissions, providing a replicable pathway for smart city construction and the achievement of China's "Dual Carbon" goals of carbon peaking and carbon neutrality.

Keywords. Traffic signal control system (TSCS), artificial intelligence traffic signal control system (AI-TSCS), carbon emissions, carbon reduction, traffic efficiency, edge computing.

1. Introduction

Against the backdrop of increasingly severe global climate change, controlling carbon emissions has become a global consensus. In August 2024, the General Office of the State Council of the People's Republic of China issued the "Work Plan for Accelerating the Construction of a Dual Control System for Carbon Emissions", highlighting transportation among key sectors for establishing a new mechanism that transforms energy-consumption dual control into carbon-emission dual control, also accelerating the establishment of a system for controlling both the total volume and intensity of carbon emissions, thereby promoting steady progress toward carbon peaking and carbon neutrality, and advancing the green transformation of development models [1]. As a major contributor to carbon emissions in China, the transportation sector accounts for approximately 11% of national total, with road transport contributing as much as 87% [2]. Measures to alleviate traffic congestion and reduce carbon emissions can be summarized as "Avoid-Shift-Improve" (ASI) framework [3]. The "Avoid" strategies reduce unnecessary travel demands, such as eliminating high-emission vehicles and restricting travel in some areas [4]. The "Shift" strategies move trips to lower-carbon modes, such as rail transit and bus rapid transit. The "Improve" strategies focuses on enhancing vehicle and fuel efficiency as well as optimizing the operational efficiency of transport system [5]. "Avoid" and "Shift" strategies often require often require policy reforms or large-scale infrastructure investments, while "Improve" strategies focus on enhancing the efficiency of existing transport systems, often offering immediate congestion relief [6]. Adopting advanced traffic-signal control systems (TSCS) is a critical "Improve" strategy that optimizes signal timing to reduce frequent acceleration, deceleration and prolonged stopping at intersections, increase travel speeds on roads, increase roadway capacity and vehicular throughput, and thereby mitigate congestion and reduce carbon emissions [7].

A growing body of research and practice has focused on reducing carbon emissions by improving TSCS. Wu et al. simulated 100 of China's most congested cities and found that big-data empowered adaptive TSCS can reduce peak-hour travel time by 11% and off-peak travel time by 8%, achieving an annual carbon reduction of 31.73 million tCO_2 and a carbon reduction rate of 6.65%. [6]; The Beijing High-Level Autonomous Driving Demonstration Zone is expected to complete the intelligent upgrading of 332 intersections within three years. Wang et al. analyzed data from three completed intersections and five road segments and found that the average annual carbon reduction per intersection is 51.71 tCO_2, while road segments achieved about twice that amount [7]. Google's Green Light project used artificial intelligence (AI) and Google Maps driving data to model traffic patterns and make recommendations for optimizing the existing traffic light plans. It has been piloted at 70 intersections across 12 cities worldwide, showing a potential reduction of up to 30% in vehicle stops and up to 10% in emissions at intersections [8]. In Tucson, Arizona, the city partnered with NoTraffic Company implemented adaptive TSCS on two critical corridors, resulting in a 23.6% reduction in overall delays and a 16% reduction in peak-hour delays, achieving an annual carbon reduction of 3,710 tCO_2 [9].

The above research and practice demonstrate that improving TSCS can effectively alleviate traffic congestion and reduce carbon emissions. However, it should be noted that these studies focus on improvements to second-generation TSCS. First-generation TSCS use fixed-time plans based on historical data—essentially static open-loop control: one or more offline timing plans are precomputed for different times of day and executed by the signal controller according to schedule. The second-generation systems are adaptive TSCS, such as SCOOT, SCATS, OPAC, and InSync, which establish a feedback loop. Intersection sensors collect real-time traffic data and upload them to a central computer. The central computer analyzes data from several past cycles based on traffic models and a plan library, evaluates new parameter sets for upcoming cycles, and then sends the resulting new timing schemes back to the intersections for execution [10,11]. While such systems enable area coordination, they also exhibit inherent limitations. (i) Objective latency: the system generates repeatable parameter sets for the near future rather than instantaneous decisions for the present. (ii) Centralized processing: evaluating new sets of parameters requires a central computer to model and analyze historical data, which leads to delays in information transfer and data processing. (iii) Reactive, model-driven logic: the system is essentially constantly evaluating the applicability of the current parameters and recalibrating it when they become invalid [10], always planning for the "near future" based on "just past" traffic conditions, resulting in an inherent delay in responding to real-time traffic changes and emergencies.

To address these limitations, the third-generation TSCS—AI-TSCS—is introduced. This system is an intelligent control system based on real-time data streams, relying on intersection edge computing units for localized decision-making, and with high-frequency dynamic scheduling capabilities. Its core features include: (i) Instantaneous objective: the system aims to make direct and immediate decisions for the current traffic situation; (ii) Decentralized decision process: instead of relying on a central computer to model historical data and optimize timing scheme, the system uses edge computing unit deployed at the intersection to perform signal control decisions based on the real-time data streams. (iii) Event-driven, stress-response logic: the system essentially makes decisions based on the current traffic conditions at high frequency, with a decision cycle of less than 100 milliseconds, which fundamentally reduces the decision delay to achieve the effect of real-time scheduling.

The AI-TSCS has been implemented on a large scale in the Xiangyang National Vehicles-to-Everything (V2X) Pilot Zone Project. This project transformed 448 intersections in the main urban area of Xiangyang into AI-TSCS, and has built a large-scale city-level V2X environment covering all 448 intersections, 740 km roads and 562 km^2 area [12]. This study investigates the effects of the AI-TSCS on improving traffic efficiency and reducing carbon emissions based on comparing various data collected before and after the project implementation.

2. Methods

2.1 Study Area and Design

(1) Temporal Scope

Due to the lack of traffic flow detectors before the project, baseline data were unavailable. In order to achieve a comparative analysis, the control mode was temporarily switched back to the pre-implementation configuration to reconstruct the baseline. The reconstructed period served as the "before" data collection window The evaluation periods were select to avoid the interference of special events on the regular traffic pattern. Therefore, the "after" period was determined to be from May 30, 2024 (Thursday) to June 5, 2024 (Wednesday); the "before" period was determined to be from June 24, 2024 (Monday) to June 30, 2024 (Sunday).

(2) Spatial Scope

Following principles of spatial balance and independence, 28 intersections were stratified and sampled from the 448 intersections as study samples. Four arterial corridors were also selected across Fancheng District, Xiangcheng District, and the High-Tech Zone: Changhong Road (2.05 km), Renmin Road (2.86 km), Shengli Street (1.34 km), and Dongfeng Motor Avenue (2.86 km). The distribution of selected intersections and road segments is shown in Figure 1.

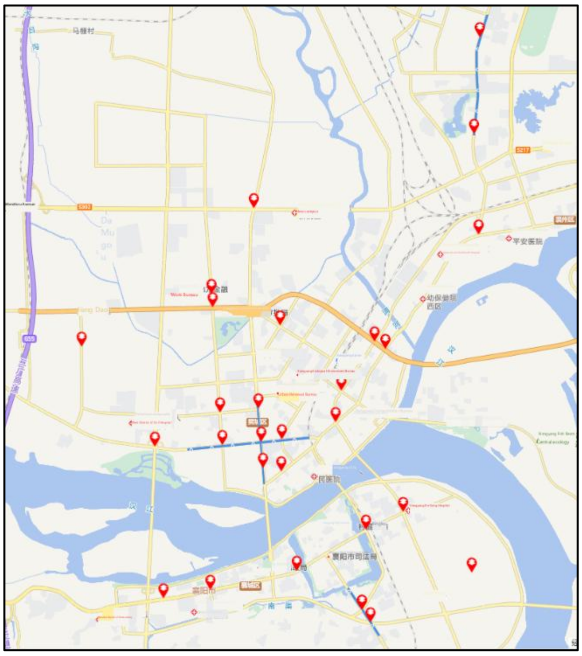


Figure 1. Intersections and Road Segments Distribution.

(3) Data Collection

Intersection Data

Vehicle motions at intersections can be divided into acceleration/deceleration phase and stopping phase. The acceleration/deceleration phase refers to the process of vehicle decelerating into and accelerating out of an intersection. In this study, a vehicle was considered to be in the acceleration/deceleration phase when its speed at the intersection was ≤ 8 km/h and > 0.2 km/h. The stopping phase refers to the process by which a vehicle stopped at an intersection. In this study, a vehicle is considered to be in the stopping phase when its speed was ≤ 0.2 km/h.

Therefore, the data collected at the intersection mainly include: traffic volume in all directions of the intersection, timestamp when a vehicle entered the deceleration phase (speed = 8 km/h during deceleration), timestamp when a vehicle ended the acceleration phase (speed = 8 km/h during acceleration or upon crossing the stop line), timestamp when a vehicle entered the stopping phases (speed = 0.2 km/h during deceleration), and timestamp when a vehicle ended the stopping phases (speed = 0.2 km/h during acceleration). Intersection data were obtained from newly installed video traffic-flow detectors and cameras in the Xiangyang National V2X Pilot Zone Project.

Road Segment Data

Vehicle motions on the road segment are considered to be uniform motion. Therefore, the collected data on road segments mainly includes: traffic volume at the starting point of each road segment, traffic volume at the ending point of each road segment, timestamp when a vehicle passed through the starting point of each road segment, and when a vehicle passed through the ending point of each road segment. Road segment data were obtained from automated red-light enforcement system of Xiangyang Traffic Police.

2.2 Carbon Accounting Methodology

This study uses the emission-factor method for carbon reduction accounting. Its basic principle is to calculate the carbon emissions or carbon reductions generated in a specific phase by multiplying the activity level data of that phase with the corresponding carbon emission factor. The calculation of carbon emission factors and carbon emission rates used in the study follows the methodology proposed by Lv et al. [13].

2.2.1 Intersections

(1) Acceleration/deceleration phase

Carbon emissions during the acceleration/deceleration phase are calculated as Equation (1):

$$E_{I\,A/D,j,t} = \sum_i VT_{\mathrm{I},i,j,t} \times T_{A/D,i,j,t} \times R_{\mathrm{A/D,\,i}} \qquad (1)$$

where,

i —The i type of vehicle;

j —The j intersection;

t —The t day;

$E_{I\,A/D,\,j,\,t}$ —Carbon emissions at the j intersection on the t day during acceleration/deceleration phases, in tons of CO_2 per day (tCO_2/ d);

$VT_{\mathrm{I},i,j,t}$ —Traffic volume of the i type of vehicle at the j intersection on the t day, in vehicles per day (vehicles/d);

$T_{A/D,\,i,\,j,\,t}$ —Acceleration/deceleration time of the i type of vehicle at the j intersection on the t day, in seconds (s);

$R_{\mathrm{A/D,\,i}}$ —Carbon emission rate of the i type of vehicle during acceleration/deceleration phases, in grams of CO_2 per second (gCO_2/s).

(2) Stopping phase

Carbon emissions during the stopping phase are calculated as Equation (2):

$$E_{I\,S,\,J,\,T} = \sum_i VT_{\mathrm{I},i,j,t} \times T_{S,\,i,\,j,\,t} \times R_{S,\,i} \qquad (2)$$

where,

$E_{I\,S,\,j,\,t}$ —Carbon emissions at the j intersection on the t day during stopping phases, in tons of CO_2 per day (tCO_2 /d);

$VT_{\mathrm{I},i,j,t}$ —Traffic volume of the i type of vehicle at the j intersection on the t day, in vehicles per day (vehicles/d);

$T_{S,\,i,\,j,\,t}$ —Stopping time of the i type of vehicle at the j intersection on the t day, in seconds (s);

$R_{S,\,i}$ —Carbon emission rate of the i type of vehicle during stopping phases, in grams of CO_2 per second (gCO_2/s).

(3) Annual carbon emissions of all intersections

The annual carbon emissions of all intersections are calculated as Equation (3):

$$E_{\mathrm{I}} = \sum_t^T \sum_j^J (E_{I\,\mathrm{A/D},\,j,\,t} + E_{I\,S,\,J,\,T}) \qquad (3)$$

where,

J —Total number of intersections;

T —Number of days in a year, taken as 365 days;

E_{I} —Annual carbon emissions of all intersections, in tons of CO_2 per year (tCO_2/yr).

2.2.2 Road Segments

(1) Daily carbon emissions of single road segment

The daily carbon emissions of single road segment are calculated as Equation (4):

$$E_{\mathrm{R},n,t} = \sum_i VT_{\mathrm{R},i,n,t} \times D_n \times EF_i \qquad (4)$$

where,

n —The n Road segment;

$E_{\mathrm{R},n,t}$ —Carbon emissions of the n Road segment on the t day, in tons of CO_2 per day (tCO_2 / d);

$VT_{\mathrm{R},i,n,t}$ —Traffic volume of the i type of vehicle in the n Road on the t day, in vehicles per day (vehicles/d);

D_n —The length of the n road segment, in kilometers (km);

EF_i —Carbon emission factor of the i type of vehicle, in kilograms of CO_2 per kilometer ($kgCO_2$ /km).

(2) Annual carbon emissions of all road segments

The annual carbon emissions of all road segments are calculated as Equation (5):

$$E_{\mathrm{R}} = \sum_t^T \sum_n^N E_{\mathrm{R},j,t} \qquad (5)$$

where,

N —Total number of road segments;

E_{R} —Annual carbon emissions for all road segments, in tons of CO_2 per year (tCO_2/yr).

2.2.3 Project-level Carbon Reduction

Given the carbon emissions before-and-after the project for all intersections and road segments, the annual carbon reduction of the urban road network is calculated as Equation (6):

$$\Delta \mathrm{E} = (E_{\mathrm{I\ Before}} + E_{\mathrm{R\ Before}}) - (E_{\mathrm{I\ After}} + E_{\mathrm{R\ After}}) \qquad (6)$$

where, $E_{\mathrm{I\ Before}}$, $E_{\mathrm{R\ Before}}$, $E_{\mathrm{I\ After}}$, $E_{\mathrm{R\ After}}$ are the total annual carbon emissions for intersections and road segments before and after the project, in tons of CO_2 per year (tCO_2/yr).

3. Result

3.1 Traffic Efficiency Analysis

3.1.1 Intersections

Changes in key indicators before and after the implementation of Xiangyang National V2X Pilot Zone Project are shown in Table 1. After implementation, although the traffic volume at the 28 intersections increased by 1.3%, the acceleration/deceleration time decreased by 15.9%, and the stopping time decreased by 17.6%, resulting in a significant improvement in traffic efficiency.

For acceleration/deceleration time, 23 out of 28 intersections (82.1%) had a reduction rate exceeding 10%; 17 intersections (60.7%) had a reduction rate exceeding 15%; and 11 intersections (39.3%) had a reduction rate exceeding 20%. The Changhong Road–Dengcheng Avenue intersection had the largest reduction rate at 33.0%. Only the Qilihe Road–Zhongyuan Road intersection failed to achieve a reduction.

For stopping time, 24 out of 28 intersections (85.7%) experienced a reduction rate exceeding 10.0%; 18 intersections (64.3%) had a reduction rate exceeding 15.0%; and 13 intersections (46.4%) had a reduction rate exceeding 20.0%. The Daqing Road–Migong Road intersection had the largest reduction rate at 31.9%. Only the Qilihe Road–Zhongyuan Road intersection failed to achieve a reduction.

Table 1. Changes in key indicators of intersections after the project.

No.	Intersection Name	Traffic Volume Change Rate	Acceleration/Deceleration Time Change Rate	Stopping Time Change Rate
1	Changhong Road–Renmin Road	2.2%	−16.3%	−14.2%
2	Changhong Road–Songhe Road	0.1%	−12.1%	−19.2%
3	Changhong Road–Jianshe Road	4.7%	−13.3%	−12.3%
4	Changhong Road–Dengcheng Avenue	2.6%	−33.0%	−30.8%
5	Renmin Road–Qianjin Road	−0.1%	−24.1%	−13.0%
6	Renmin Road–Hanjiang Road	1.6%	−16.1%	−19.4%
7	Renmin West Road–Wolong Avenue Frontage Road	−11.1%	−9.4%	−10.2%
8	Daqing Road–Migong Road	2.5%	−20.9%	−31.9%

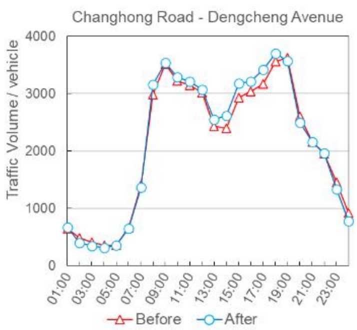
No.	Intersection Name	Traffic Volume Change Rate	Acceleration/Deceleration Time Change Rate	Stopping Time Change Rate
9	Daqing Road–Changzheng Road	−0.1%	−6.8%	−21.7%
10	Daqing Road–Qinghe Road	−4.3%	−15.8%	−27.3%
11	Changzheng Road–Danjiang Road	2.2%	−23.8%	−26.6%
12	Changzheng Road–Qinghe Frontage Road	0.9%	−0.5%	−4.8%
13	Hanjiang Road–Songhe Road	1.9%	−6.8%	−7.3%
14	Hanjiang Road–Zhongyuan Road	0.1%	−19.7%	−16.1%
15	Hanjiang Road–Jiangshan South Road	6.6%	−17.8%	−21.8%
16	Qilihe Road–Zhongyuan Road	4.2%	2.3%	9.6%
17	Qilihe Road–Zhonghang Avenue	7.6%	−25.5%	−27.6%
18	Panggong Road–Fengchu Avenue	3.0%	−22.6%	−29.1%
19	Dong Street–Huancheng East Road	5.5%	−29.0%	−25.8%
20	Tanxi Road–Tiefosi Road	0.4%	−12.8%	−22.9%
21	Tanxi Road–Pipashan Road	2.2%	−13.5%	−13.2%
22	Tanxi Road–Shuanghu Road	1.7%	−12.3%	−23.9%
23	Shengli Street–Huancheng East Road	−0.6%	−32.3%	−24.2%
24	Shengli Street–Huancheng South Road Frontage Road	0.6%	−20.6%	−19.0%
25	Yuliangping Avenue–Jianghua Road	17.9%	−24.3%	−31.7%
26	Hangkong Road–Checheng South Road	0.5%	−12.6%	−6.0%
27	Dongfeng Motor Avenue–Chechenghu South Road	0.5%	−17.9%	−14.2%
28	Dongfeng Motor Avenue–Xincheng Road	7.4%	−20.6%	−15.5%
28 intersections		**1.3%**	**−15.9%**	**−17.6%**

Changhong Road–Dengcheng Avenue, Hanjiang Road–Songhe Road, and Hanjiang Road–Hanshan South Road were selected to make time-of-day comparisons in Figure 2–Figure 4. After the project, although traffic volumes of the three intersections increased slightly, acceleration/deceleration time and stopping time decreased to varying degrees at different times throughout the day.

Changhong Road–Dengcheng Avenue has significantly reduced acceleration/deceleration time and stopping time during the morning peak (7:00–9:00) and evening peak (17:00–19:00), for example, between 18:00 and 19:00, the acceleration/deceleration time decreased by 38.7% and the stopping time by 40.0%, which makes the peak period no longer significantly increase compared with the off-peak period.

Although acceleration/deceleration time and stopping time of Hanjiang Road–Songhe Road did not achieve a significant decrease during the peak period. However, overall, it still achieved a certain degree of decline at different periods throughout the day.

Hanjiang Road–Hanshan South Road has significantly reduced acceleration/deceleration time and stopping time during the peak period. For example, between 18:00 and 19:00, acceleration/deceleration time decreased by 26.0% and stopping time decreased by 35.7%. Overall, the reductions were relatively uniform at different times throughout the day.



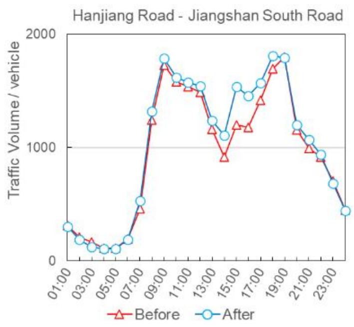


Figure 2. Comparison of Traffic Volume at Intersections (Before vs. After).

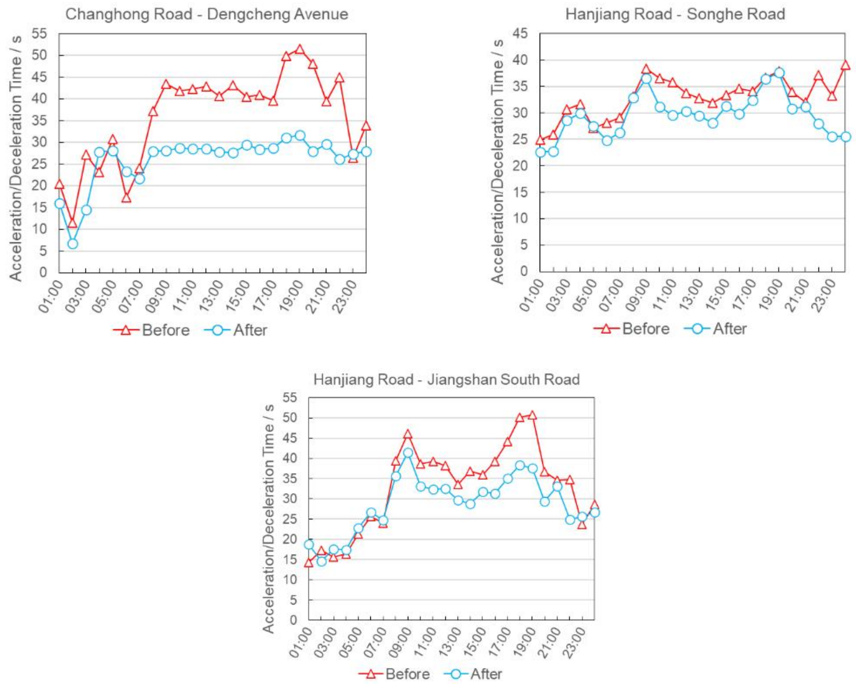


Figure 3. Comparison of Acceleration/Deceleration Time at Intersections (Before vs. After).

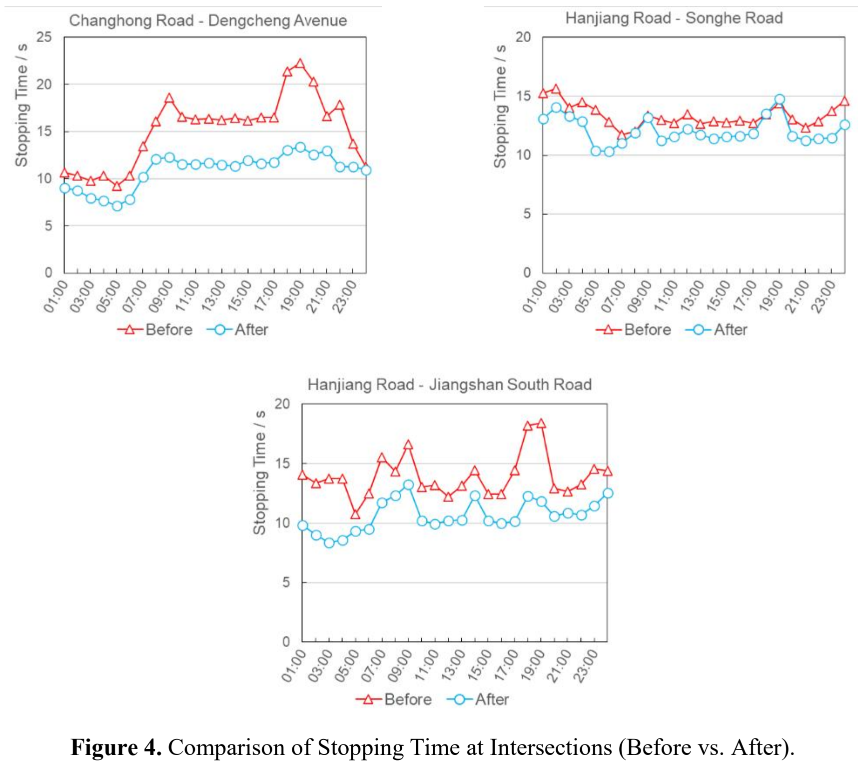


Figure 4. Comparison of Stopping Time at Intersections (Before vs. After).

3.1.2 Road Segments

The changes of the key indicators for the four selected road segments before and after the implementation of Xiangyang National V2X Pilot Zone Project are shown in Table 2. After the project, although the traffic volume of the four road segments increased slightly by an average of 0.4%, the average speed during peak periods increased by 11.4%, the average speed during off-peak periods increased by 16.7%, and the average speed throughout the day increased by 15.2%, resulting in a significant improvement in traffic efficiency.

For average speed during peak hours, 3 out of 4 segments (75.0%) had a growth rate exceeding 10.0%; 1 segment (25%) had a growth rate exceeding 15%. Dongfeng Motor Avenue had the largest growth rate at 16.0%.

For average speed during off-peak hours, all 4 segments (100.0%) had a growth rate exceeding 10.0%; 3 segments (75%) had a growth rate exceeding 15%. Changhong Road had the largest growth rate at 21.1%.

Table 2. Changes in Key Indicators of Road Segments After the Project.

No.	Road Segment Name	Traffic Volume Change Rate	Average Speed Change Rate During Peak Hours	Average Speed Change Rate During Off-peak Hours	Average Speed Change Rate During the Day
1	Changhong Road	0.2%	11.1%	21.1%	18.3%
2	Renmin Road	0.2%	8.5%	18.1%	15.4%
3	Shengli Street	0.4%	10.0%	14.7%	13.4%
4	Dongfeng Motor Avenue	1.2%	16.0%	12.9%	13.7%
4 Road Segments		**0.4%**	**11.4%**	**16.7%**	**15.2%**

Changhong Road, Shengli Street and Dongfeng Motor Avenue were selected for week-level comparisons, as shown in Figures 5 and 6. After the project, the average speeds of the 4 road segments increased to varying degrees. During peak periods, the largest increase in average speed was on Changhong Road on Thursday, with an increase rate of 26.4%. During off-peak periods, the largest increase in average speed was on Changhong Road on Thursday, with an increase rate of 41.0%.

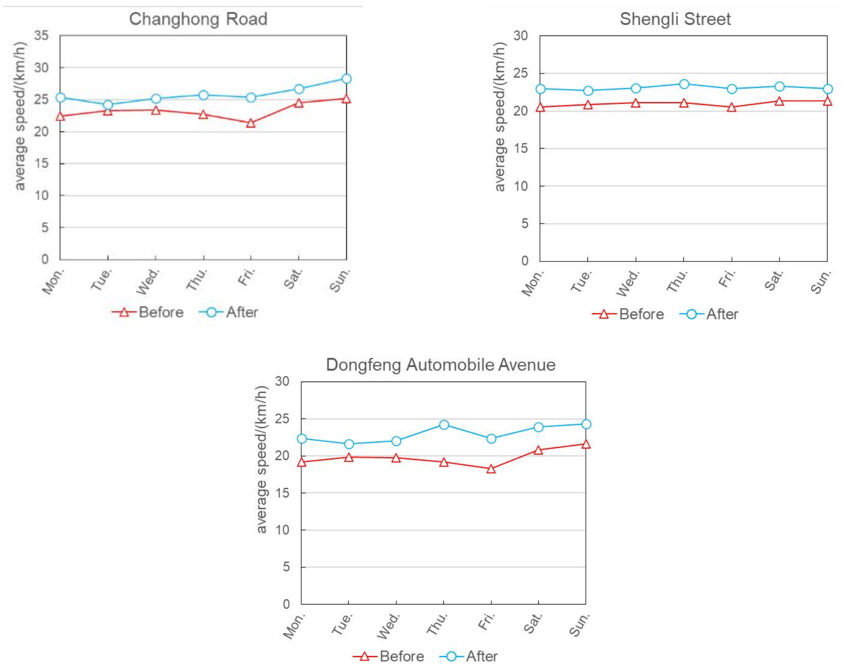


Figure 5. Comparison of Average Speed during Peak Periods (Before vs. After).

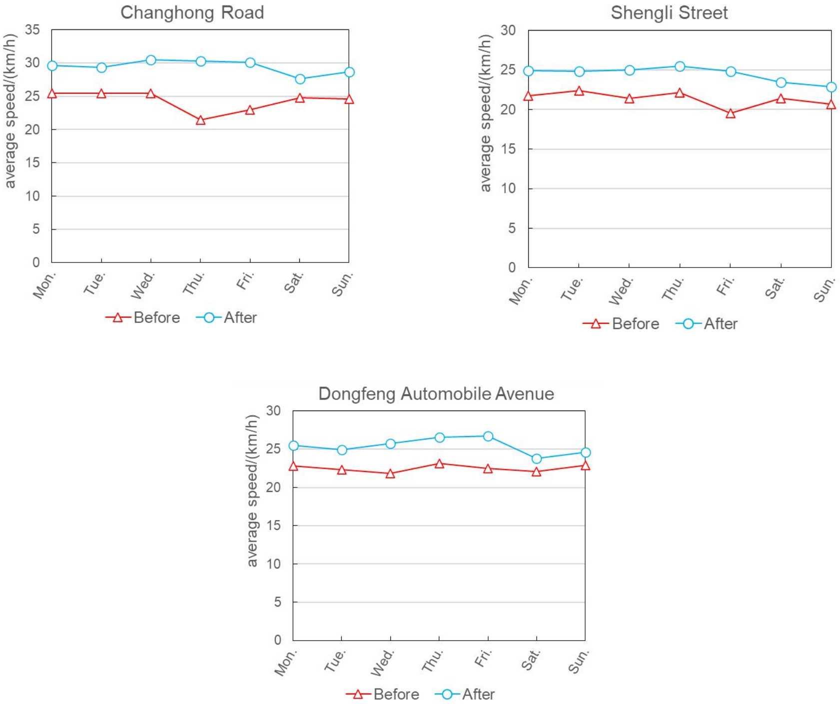


Figure 6. Comparison of Average Speed during Off-peak Periods (Before vs. After).

3.2 Carbon Reduction Analysis

3.2.1 Intersections

The annual emissions and reductions at the 28 intersections before and after the Xiangyang National V2X Pilot Zone Project are shown in Table 3. On average, annual carbon emissions decreased from 965.3 tCO_2 before the project to 817.4 tCO_2 after the project, resulting an average annual carbon reduction of 148.0 tCO_2, with an average reduction rate of 15.3%.

24 out of 28 intersections (85.7%) had a carbon reduction rate exceeding 10%; 15 intersections (53.6%) had a carbon reduction rate exceeding 15%; 9 intersections (32.1%) had a carbon reduction rate exceeding 20%. Shengli Street–Huancheng East Road has the largest carbon reduction rate at 30.8%; Only Qilihe Road–Zhongyuan Road failed to achieve carbon reduction.

Table 3. Annual Emissions and reductions at Intersections.

No.	Intersection name	Emissions before the project (tCO_2)	Emissions after the project (tCO_2)	Reductions (tCO_2)	Reduction Rate
1	Changhong Road–Renmin Road	1935.9	1673.6	262.3	13.6%
2	Changhong Road–Songhe Road	1580.8	1356.6	224.3	14.2%
3	Changhong Road–Jianshe Road	1239.0	1128.1	111.0	9.0%
4	Changhong Road–Dengcheng Avenue	1602.8	1111.0	491.8	30.7%
5	Renmin Road–Qianjin Road	1626.2	1289.7	336.5	20.7%
6	Renmin Road–Hanjiang Road	1045.5	880.5	165.0	15.8%
7	Renmin West Road–Wolong Avenue Frontage Road	516.9	415.0	101.8	19.7%
8	Daqing Road–Migong Road	346.2	274.7	71.5	20.6%
9	Daqing Road–Changzheng Road	2087.9	1839.5	248.4	11.9%
10	Daqing Road–Qinghe Road	1685.4	1305.8	379.6	22.5%
11	Changzheng Road–Danjiang Road	1092.7	839.9	252.8	23.1%
12	Changzheng Road–Qinghe Frontage Road	1533.9	1521.2	12.7	0.8%
13	Hanjiang Road–Songhe Road	978.0	927.0	51.0	5.2%
14	Hanjiang Road–Zhongyuan Road	907.2	738.1	169.1	18.6%
15	Hanjiang Road–Jiangshan South Road	676.9	586.0	90.9	13.4%

No.	Intersection name	Emissions before the project (tCO_2)	Emissions after the project (tCO_2)	Reductions (tCO_2)	Reduction Rate
16	Qilihe Road–Zhongyuan Road	1234.2	1337.8	-103.6	-8.4%
17	Qilihe Road–Zhonghang Avenue	267.4	212.5	54.9	20.5%
18	Panggong Road–Fengchu Avenue	805.8	621.7	184.1	22.8%
19	Dong Street–Huancheng East Road	896.6	681.4	215.1	24.0%
20	Tanxi Road–Tiefosi Road	380.9	323.5	57.4	15.1%
21	Tanxi Road–Pipashan Road	548.2	485.1	63.1	11.5%
22	Tanxi Road–Shuanghu Road	568.4	487.6	80.8	14.2%
23	Shengli Street–Huancheng East Road	747.9	517.8	230.1	30.8%
24	Shengli Street–Huancheng South Road Frontage Road	709.5	569.4	140.1	19.7%
25	Yuliangping Avenue–Jianghua Road	135.8	117.7	18.0	13.3%
26	Hangkong Road–Checheng South Road	1213.9	1082.2	131.7	10.8%
27	Dongfeng Motor Avenue–Chechenghu South Road	427.5	356.9	70.7	16.5%
28	Dongfeng Motor Avenue–Xincheng Road	237.9	205.8	32.1	13.5%
Average of 28 Intersections		**965.3**	**817.4**	**148.0**	**15.3%**

The Xiangyang National V2X Pilot Zone Project has completed 448 intersections. Based on this coverage, the annual carbon emissions at the intersections are estimated to have been 432,465.6 tCO_2 before the project and 366,176.5 tCO_2 after the project, resulting in an annual carbon reduction of 66,289.1 tCO_2 at the intersections.

3.2.2 Road Segments

The annual emissions and reductions on four road segments before and after the Xiangyang National V2X Pilot Zone Project are shown in Table 4. The average annual carbon reduction per kilometer is 206.2 tCO_2/km, with an average carbon reduction rate is 6.9%.

All four segments (100.0%) had a carbon reduction rate exceeding 5.0%, with Changhong Road achieving the highest carbon reduction rate at 7.5%.

Table 4. Annual Emissions and reductions on Road Segments.

No.	Road segment name	Emissions before the project (tCO_2)	Emissions after the project (tCO_2)	Reduction (tCO_2)	Reduction per km (tCO_2/km)	Reduction rate
1	Changhong Road	9491.0	8777.7	713.3	348.0	7.5%
2	Renmin Road	10384.7	9613.3	771.3	269.7	7.4%
3	Shengli Street	2595.7	2444.1	151.6	113.1	5.8%
4	Dongfeng Motor Avenue	4697.4	4455.0	242.4	206.2	5.2%
4 Road Segments		**27168.8**	**25290.2**	**1878.6**	**206.2**	**6.9%**

The Xiangyang National V2X Pilot Zone Project has completed coverage of 740 kilometers. Based on this coverage, the annual carbon emissions on road segments are estimated to have been 2,206,903.7 tCO_2 before the project and 2,054,306.7 tCO_2 after the project were, resulting in an annual carbon reduction of 152,597.0 tCO_2.

3.2.3 Project-level Carbon Reduction

Aggregating carbon emissions from intersections and road segments, the total annual carbon emissions before the Xiangyang National V2X Pilot Zone Project were 2,639,369.3 tCO_2, and 2,420,483.2 tCO_2 after the project. The project achieved an annual carbon reduction of 218,886.1 tCO_2, corresponding to a carbon reduction rate of 8.3%, demonstrating a significant effect in reducing urban traffic-related carbon emissions.

4. Discussion

4.1 Effectiveness

A simulation study of the 100 most congested cities in China by Wu et al. [6] shows that implementing the big-data empowered adaptive traffic signal system can reduce 6.65% CO_2 emissions, which is lower than the 8.3% in this project.

According to the complete dataset of that simulation study [6], although Xiangyang ranks only 81st baseline emissions among the 100 cities, its carbon reduction rate ranks 23rd. As noted in the simulation study, cities with higher baseline emissions show greater absolute reduction potential. Among the 22 cities with higher carbon reduction rates than Xiangyang, 17 have baseline emissions more than 20% higher than Xiangyang, 15 are more than 50% higher, and 10 are more than 100% higher. Therefore, Xiangyang achieved a high carbon reduction rate with low baseline emissions, indicating that AI-TSCS have a significant effect on reducing carbon emissions.

Among practical implementation projects, Beijing's project [7] plans to upgrade 332 intersections within three years. However, the current evaluation covers only three intersections, which is too small a sample to generalize. Google's Green Light project [8] pilots 70 intersections across 12 cities and indicates a potential for up to 10% reduction in carbon emissions at intersections. However, these intersections are scattered across multiple cities, making the results more likely reflect improvements at individual intersections or within small areas, and do not represent the results after citywide coverage. If compared with a single intersection, 24 of 28 sample intersections (86.7%) of our project achieve a carbon reduction rate greater than 10%. Tucson's project [9] reports a 16% reduction in peak delay and a 23.6% reduction in overall delay, which is better than our results, but it implemented only two major corridors rather than on a citywide scale.

Overall, compared with simulation research and implementation projects based on second-generation adaptive TSCS, the present project, as third-generation AI-TSCS projects that covering an entire main urban area with 448 intersections, has achieved better results in improving traffic efficiency and reducing carbon emissions. It provides a replicable pathway for smart city development and the achievement of China's "Dual Carbon" goals.

4.2 Limitations and Future Work

This study has some limitations. First, due to the lack of effective traffic flow detectors before the project, this study uses the baseline scenario was reconstructed by switching the system back to the original control mode. Although this is a commonly used approach in engineering evaluations, it may not perfectly reproduce historical traffic conditions. Second, this study is based on sampling of representative intersections and road segments. Although the results can reflect the overall trend, the accurate carbon reduction of the entire road network still requires validation through larger-scale monitoring data. Third, the accuracy of the emission factor method used in this study depends on the accuracy of the CO_2 emission factor. If the CO_2 emission factor used differs from Xiangyang's actual situation, errors may occur in the calculation results.

Based on the above limitations, future work in this study may include: First, conducting long-term monitoring that covers the entire road network to obtain more comprehensive and accurate traffic data of intersections and segments; Second, conducting localized calibration research on CO_2 emission factors in Xiangyang to calibrate the calculation results of the emission factor method; Third, establishing a remote-sensing-based model for inverting traffic carbon emissions, and recalculation of carbon reductions as a reference for verifying the results of this study.

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