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Potential of Ecological Benefits for the Continuous Flow Intersection

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ABSTRACT

Energy conservation and emission reduction from the transportation sector are of great significance in coping with the global energy and environmental crisis. As the bottleneck of urban road traffic, intersection burdens the urban environment greatly. When the volume of left-turn traffic is large, the continuous flow intersection (CFI) can effectively improve intersection operation efficiency. This paper first put forward the definition and application conditions of CFI. Then its mechanism for energy saving and emission reduction was analysed. CFI transformation was designed taking a typical intersection in Xi'an as an example. Operating efficiency, energy consumption and emissions of the intersection before and after CFI transformation were evaluated using the VISSIM model. The results show that energy consumption and emissions in the intersection are greatly reduced after CFI transformation. Queue length is reduced by more than 41%. Energy consumption and pollutant emission are reduced by about 8%. Through the simulation analysis, the emission reduction benefits most when the volume of left-turn traffic is 80%–85% of the design capacity, and the ratio of left-turn traffic over through traffic is maintained between 50% and 100%. This study suggests that CFI is suitable for large-scale promotion with careful examination.

KEYWORDS

sustainable transportation; intersection design; continuous flow intersection; efficiency improvement; VISSIM simulation.

1. INTRODUCTION

The share of energy consumption from the transportation sector has risen from second place in the 1990s (about 25%) to first place in 2018 (29%), overtaking the industrial sector (see *Figure 1*). Meanwhile, the transportation sector is now the second-largest emitter of CO_2 and is growing steadily, as shown in *Figure 2*. With the increasing number of cars per capita in developing countries, energy consumption and emissions from the transportation sector will continue to increase in the coming years. Therefore, a sustainable transportation system can make a great contribution to tackling global climate change and the energy crisis. The potentials for energy and emission reduction from vehicle energy efficiency improvement, green travel mode structure change [1], alternative clean fuels shift [2] and intelligent control [3] have been addressed in recent literature. The potential from the infrastructure form side [4], however, is little mentioned.

Intersection, as the bottleneck of urban road traffic, burdens the urban environment due to traffic delay, energy consumption and emissions caused by vehicle brake-start behaviours. Improving intersection efficiency could contribute to a sustainable transportation system. Continuous flow intersection (CFI) [5–7] is a promising intersection design when left-turn traffic is large. CFI works in this way: when left-turn traffic is about to arrive at an intersection, a pre-signal light is set at an appropriate position to make them move to the opposite exit lane in advance. This left-turn traffic waits for the signal light to turn green at the main signal intersection, then is released together with through traffic (as shown in *Figure 3*). This design makes full use of the space and time resources of the intersection. By reducing the conflict between left-turn vehicles and vehicles in other directions, the primary intersection does not need to set the dedicated signal phase for left-turn traffic, thus shortening the signal cycle. China's first CFI intersection was successfully transformed in 2017 on Shenzhen Caitian-Fuhua Road, which greatly relieved the intersection traffic pressure at that time.

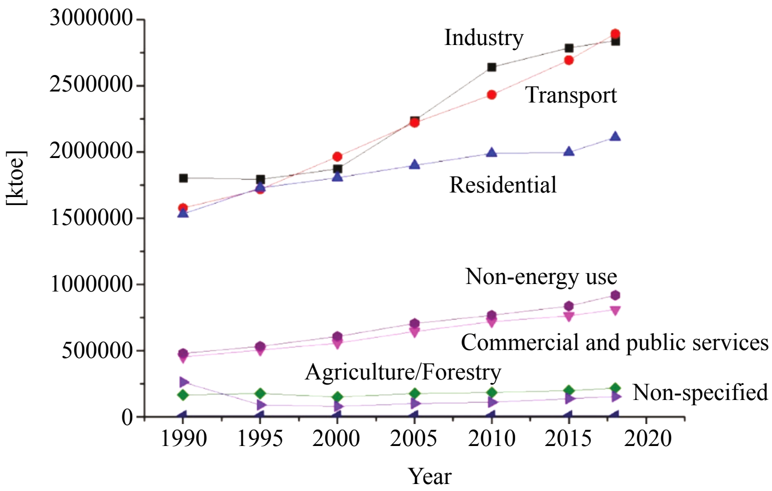


Figure 1 – Total final energy consumption by sector, world 1990–2018 (Source: IEA)

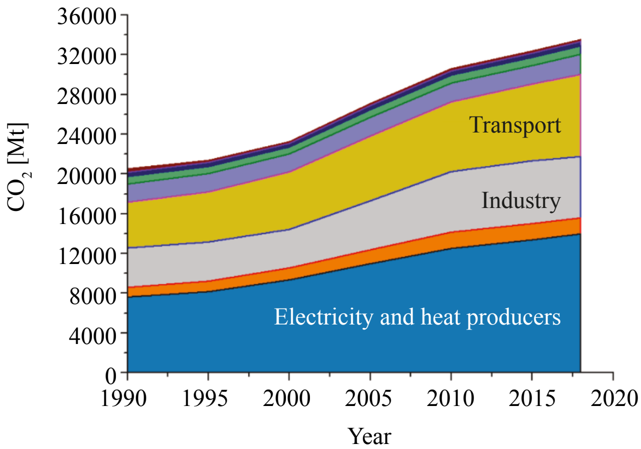


Figure 2 – CO_2 emissions by sector, world 1990–2018 (Source: IEA)

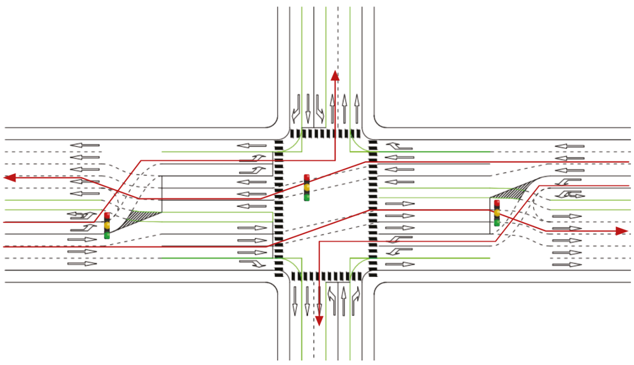


Figure 3 – Diagram of continuous flow intersection (taking the east-west directions as an example)

Initially, studies on CFI put more emphasis on operating efficiency, focusing on intersection geometric design and signal timing optimisation [8, 9]. To improve the capacity of intersections, Coates et al. [10] improved the geometric design of intersections and established an optimisation model. Subsequently, considering pedestrian safety, Coates et al. [11] reassessed the impact of intersection geometric design on CFI operation efficiency. Among geometric design elements, displaced-left lane length design is a research focus area [12]. Moreover, signal timing optimisation of CFI has also attracted the attention of scholars [13–17]. In 2015, Zhao et al. [18] proposed a generalised lane-based comprehensive design optimisation model for CFI types, lane markings, left-turn lane length and signal timing. A large number of numerical analysis results show the effectiveness of this method. In the same year, Sun et al. [19] proposed a simplified continuous flow crossover design (called CFI-Lite), which can let left-turn and through traffic go simultaneously without installing a sub-signal light, laying a foundation for the further promotion and application of CFI.

With the implementation and gradual promotion, safety and mobility assessment are important considerations. In 2020, Qu et al. [20] studied the operation safety of CFI in the United States based on its accident data from 2011 to 2018. The results showed that although some new problems emerged, such as traffic signs and access control management, CFI significantly reduced accidents related to left and right turns and did not increase the overall collision frequency. It is suggested that traffic engineers need to carefully consider different aspects of CFI design, including access management, traffic signal coordination and driver acceptance in the implementation of CFI. In 2021, Ahmed et al. [21] evaluated the mobility of pedestrian and bicycle treatments at complex CFIs.

Although the studies above confirmed the high operating efficiency and safety of CFI, the existing studies did not mention the potential of CFI in energy conservation and emission reduction, which directly determines whether CFI can be vigorously promoted and applied in the context of carbon peak and carbon neutral. It has been widely suggested that CFI can decrease travel time and delay vehicles passing through the intersection. As a result, traffic flow is generally more stable, decreasing fuel consumption and emissions. However, due to the existence of the sub-intersection, left-turn vehicles and some cleared-through vehicles increased the number of stops. Due to constant braking and starting (especially starting) behaviours, fuel consumption and emissions will increase. The final energy-saving and emission-reduction effect of CFI depends on the tradeoff between the pros and cons mentioned above.

The purpose of this paper is to identify the energy-saving and emission-reduction potential of CFI and to put forward standards for CFI transformation from traditional intersections to enhance environmental benefits. A typical intersection in Xi'an city, China, was selected for CFI transformation, including geometric design and signal control design. Finally, a quantitative analysis based on the VISSIM simulation was conducted. Operational efficiency, energy consumption and emission differences were compared before and after the intersection transformation. Quantitative relationships presented can provide transportation professionals and officials with more accurate and precise guidance to facilitate better decisions in considering, evaluating and designing a CFI.

2. METHODOLOGY

2.1 Overview

To ensure the operation efficiency of CFI, transformed intersections should meet certain index requirements, as shown in *Table 1*. According to the requirements, an intersection in Beidajie, Xi'an, Shaanxi Province, China, was selected as the object of CFI transformation. The current situation of the intersection is shown in the third column of *Table 1*. The current signal phase design of the intersection is illustrated in *Figure 4*. Signal period, signal duration and current traffic volume are shown in *Tables 2 and 3*, respectively. The data was collected by on-site video recording in the evening peak hour (from 17:00 to 18:00).

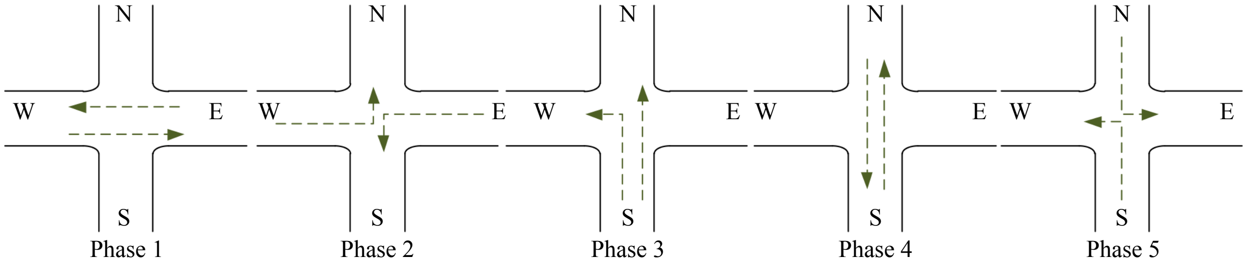


Figure 4 – Current signal phases of Beidajie intersection

Table 1 – Index requirements for CFI transformation

Indicators	Ideal situations for CFI transformation	The situation for the Beidajie intersection
Intersection form	Symmetrical four-way intersection (√) - Multi-way intersection (×): the management is too complicated - T-intersection(×): cannot maximise the effect Short-spaced intersection (×): have requirements for the lane length More lanes (√): large transformation space and small influence on traffic flow	Symmetrical four-way intersection Long-spaced intersection No. of lanes: North (11 lanes in both directions). South (10 lanes in both directions)
Pedestrian and non-motor traffic	Intersections with underground or above-ground crossings: reduce the impact of pedestrian and non-motor traffic	Underground passage
Bus stop	Not suitable for setting up a bus station near the intersection: - Bus parking behaviour will induce traffic congestion in nearby road sections. - A bus stop could result in a shortage of lane-changing distances for buses.	While there is a bus stop near the intersection, it can be displaced due to enough lane length.
Traffic flow	Through traffic > 500 pcu/h Left-turn traffic > 250 pcu/h Left-turn traffic / through traffic > 30%	See *Table 3*

Table 2 – Current signal phase design (period: 215 s)

Signal phase	Function	Green time [s]	Yellow time [s]	Red time [s]
1	East-West direction: through and right turn	50	3	162
2	East-West direction: left turn	28	3	184
3	South to North: through, left turn, and right turn	26	3	186
4	South-North: through and right turn	67	3	145
5	South-North: left turn	29	3	183

Table 3 – Current traffic flow of the intersection

Approaches	Direction	No. of lanes	Traffic flow	Capacity	Saturation	Left/straight proportion
East	Left	2	236	256	0.92	0.34
	Straight	2	689	623	1.11	
	Right	1	100	-	-	
West	Left	1	113	128	0.88	0.21
	Straight	3	549	935	0.59	
	Right	1	490	-	-	
South	Left	2	503	503	1.00	0.55
	Straight	2.5	915	1441	0.64	
	Right	1.5	168	-	-	
North	Left	2	296	265	1.12	0.31
	Straight	3.5	952	1489	0.64	
	Right	1.5	60	-	-	

2.2 Theoretical models

Section length design

According to the requirements shown in *Table 1*, we only designed the displaced left-turn lanes for the South-North direction, as shown in *Figure 5*. Section length design (Jiang et al. 2019) includes three parts: displaced lane section l_1, crossover lane section l_2, and storage lane section l_3.

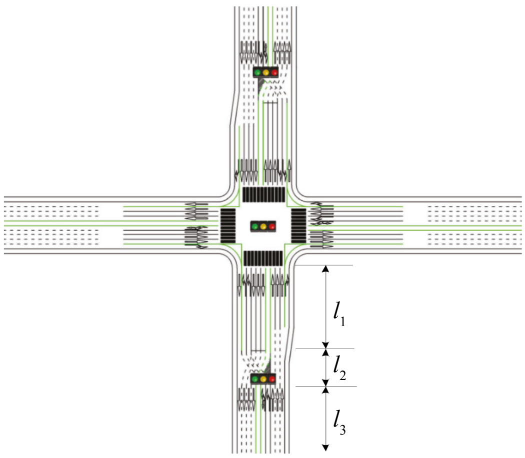


Figure 5 – Illustration of lane section length in CFI

Length of displaced left-turn lane section l_1: The section length of displaced left-turn lanes is related to the number of left-turn vehicles in this direction. If it is too short, left-turn vehicles will overflow into crossover lanes, resulting in congestion. As suggested by Jiang et al. (2019), l_1 should satisfy the following condition.

$$l_1 \geq \frac{kQ_{el}h_s}{mn} \quad (1)$$

where l_1 is the section length of displaced left-turn lanes (m); Q_{el} is the traffic flow from the South-North direction (pcu); h_s is the headway of left-turn vehicles in the queue (m); k is the non-uniformity coefficient of left-turn vehicles that arrived in one signal period. Commonly, it will take the value from 1.5 to 2. m is the number of left-turn lanes; n is the number of signal cycles within one hour.

Length of crossover lane section l_2: At the secondary intersection, vehicles need to enter the displaced left-turn lanes through crossover lanes. The length of the crossover lane section is related to lane width, double yellow lines width, and minimum turning radius length of vehicles. l_2 should satisfy the following condition (Jiang et al. 2019):

$$l_2 \geq 2\sqrt{r^2 - (r - s)^2}, \quad s = \frac{2W_1 \pm W_2}{2} \tag{2}$$

where l_2 is the section length of crossover lanes (m); r is the minimum turning radius of vehicles (m); s is the intermediate variable in the geometric calculation process; W_1 is the width of one lane (m); W_c is the width of double yellow lines (m).

Length of storage lane section l_3: Since displaced left-turn vehicles need to stop once at the secondary intersection, it is necessary to design the section length for storage lanes (l_3). l_3 should satisfy the same requirement as shown in *Equation 1*. At the same time, the sum of three lengths should satisfy the following requirement:

$$l_1 + l_1 + l_1 \leq l \tag{3}$$

where l is the length of the intersection with the adjacent upstream intersection (m).

Traffic signal design

Signal phase: Compared with the traditional intersection, CFI can let left-turn traffic and through traffic from the South-North direction go simultaneously, reducing the number of signal phases. However, a secondary signal is required. The phase design of this two-way control is shown in *Figure 6*.

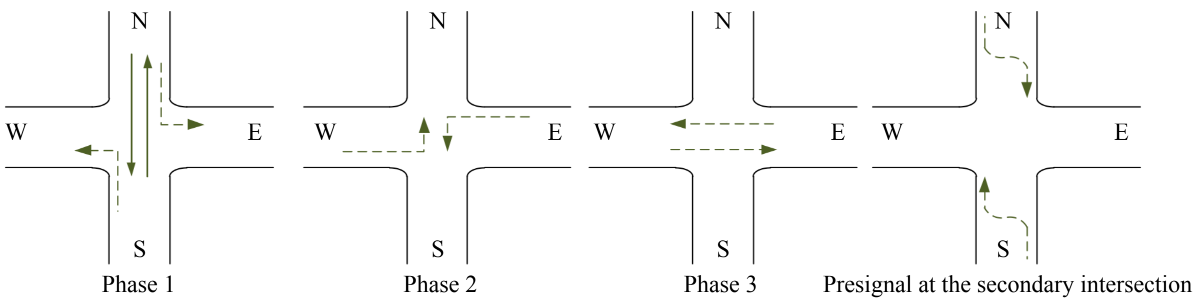


Figure 6 – Phase design of the two-way control

Signal cycle: Webster model is adopted to design the optimal signal cycle time at the intersection. The formulas are displayed from *Equations 4–7*:

$$C_0 = \frac{1.5L_{lost} + 5}{1 - Y} \tag{4}$$

$$L_{lost} = \sum_{i=1}^{n} (l_s + I_i + A_i) \tag{5}$$

$$Y = \sum_{i=1}^{n} \max(y_{i1}, y_{i2}, \cdots) \tag{6}$$

$$y_{i1} = \frac{v_{i1}}{S_{i1}} \tag{7}$$

where C_0 (s) is the optimal signal cycle time; L_{lost} (s) is the total lost time; Y is the sum of the maximum flow ratios of all phases constituting the period; l_s is the vehicle start time, generally 2, 3 s; I_i (s) is the green interval time for phase i, which is the sum of yellow light time and all-red time; A_i is the yellow light time, usually taking 3 s. n is the number of phases; y_{i1} is the ratio of traffic flow for the first traffic direction (with the maximum flow) in phase i; v_{i1} is the actual arrival flow rate of the first traffic direction in phase i (pcu/h);

S_{i1} is the saturation flow rate of the first traffic direction in phase i (pcu/h). Based on the information in *Figure 6* and *Table 3*, we can obtain the optimal signal cycle is 181 s.

Signal timing: According to the Webster model, green time for each phase can be calculated based on *Equations 8 and 9*:

$$G_e = C_0 - L_{lost} \tag{8}$$

$$g_{ei} = G_e \cdot \frac{y_i}{Y} \tag{9}$$

where g_{ei} is the effective green time for phase i (s). The signal timing of CFI in this case study is illustrated in *Figure 7*. Moreover, to improve the efficiency of the intersection and reduce the number of vehicle stops, the relationship between the main signal and the pre-signal should meet the requirements shown by *Equations 10 and 11*:

$$t_4 - t_1 \geq \frac{l_1 + l_2 + l_3}{V_{el}} \tag{10}$$

$$t_4' - t_2 \leq \frac{l_1 + l_r}{v_{ss}} \tag{11}$$

where t_1, t_2, t_3, t_4' are shown in *Figure 7*; l_r is the path length of left-turn vehicles from eastern and western directions at the intersection (m); V_{el} is the average speed of vehicles turning left from eastern and western directions (m/s); v_{ss} is the average speed of through vehicles from southern and northern directions (m/s). *Equation 10* is to guarantee that left-turn vehicles from eastern and western directions entering the intersection at phase 2 can completely pass the crossover lane section, avoiding the second stop. *Equation 11* is to allow displaced left-turn lanes to be closed later than the opening of phase 1. However, the time gap has an upper bond as shown in *Equation 11*.

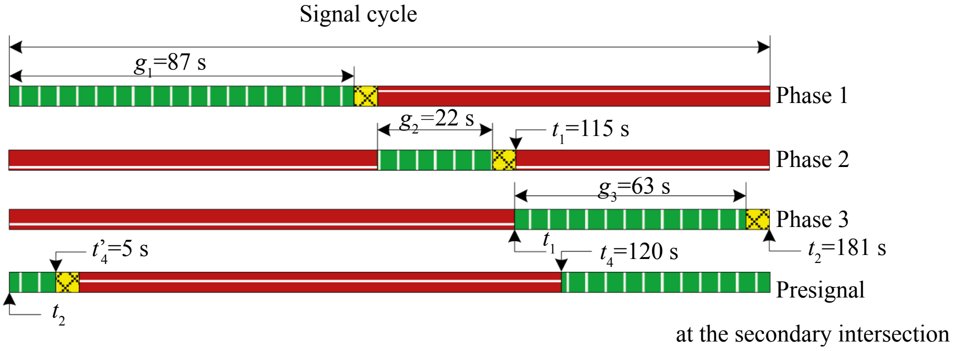


Figure 7 – Signal timing for the CFI

3. SIMULATION EXPERIMENT

In this study, the VISSIM simulation model was used to evaluate the energy-saving and emission-reduction potential of CFI transformation. To make simulation results comparable, it is necessary to ensure that the current situation in the simulation world is consistent with what is in the actual situation. Therefore, parameters in the simulation software need to be calibrated. Referring to the method proposed by Sun and Yang [22], the parameter calibration process is shown in *Figure 8*.

In the calibration process, two indicators were selected to judge whether the simulation world is consistent with what is in the real world. The travel time of vehicles required to pass 200 m through the intersection from the east to the west was selected as one verification indicator. Moreover, the maximum queue length of through traffic at the east approach was selected as another indicator. The two indicators can be easily measured in the actual road network and can be simulated in VISSIM. The core parameters of driving behaviour in VISSIM are those from a car-following model and lane-changing model [22], as shown in *Tables 4 and 5*, respectively. We only calibrated these parameters. The influence of each parameter, however, is different. Parameters with higher sensitivity should be selected for calibration. We used variance analysis to select parameters with high sensitivity. At last, the orthogonal experiment was used to determine the optimal parameter combination.

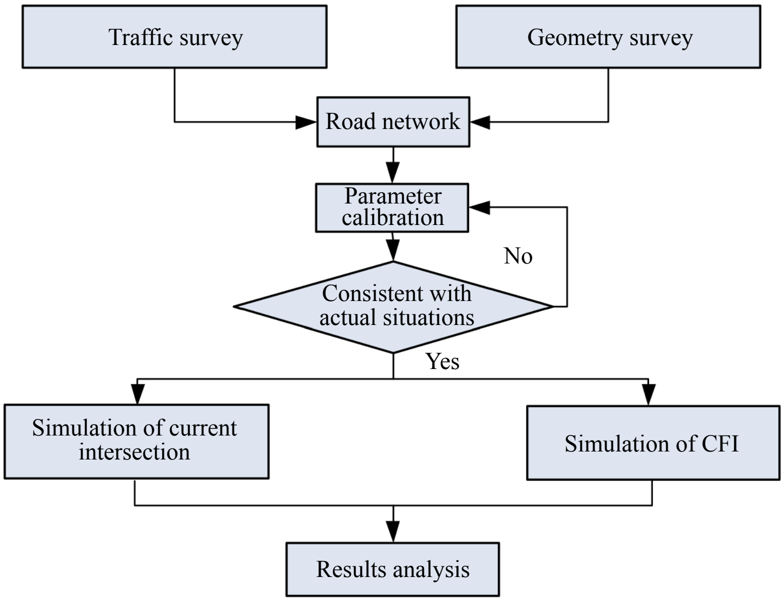


Figure 8 – Calibration process

Table 4 – Parameters in the car following model

Parameter	Description
Number of visible vehicles ahead	The number of vehicles that can be seen in front of the vehicle. The default value is 2.
Maximum forward-looking distance	The maximum distance that a driver can observe when looking ahead. The default value is 250 m.
Mean stop spacing	The average resting distance between the front and rear vehicles. The default value is 2 m.
An addition to the safe distance	As a factor participating in the calculation of safe distance. The default value is 2 m.
Multiples of the safe distance	As a factor participating in the calculation of safe distance. The default value is 3 m.

Table 5 – Parameters in the lane-changing model

Parameter	Description
The wait time before eliminating	The maximum amount of time a vehicle can wait for a lane change on a road segment before being removed from the network. The default value is the 60 s.
Minimum vehicle spacing	The minimum spacing in a stop required to successfully change lanes for the vehicle behind. The default value is 0.5 m.
Maximum deceleration	Maximum deceleration of the vehicle. The default value is -3 m/s^2.
Acceptable deceleration	When below the maximum deceleration, the desired deceleration is taken as the maximum deceleration. The default value is -1 m/s^2.

We used the ANOVA approach to select calibrated parameters based on the simulation results. The simulation duration time was set to be 4000 s. 400 s were used to warm up the intersection. After that, simulation results were saved once every 600 s, for a total of 6 times. The parameter representing multiples of the safety distance of a vehicle was taken as an example to show the analysis process. Values of the parameter and simulated travel time in different periods are shown in *Table 6*. Simulated maximum queue lengths in the different periods are shown in *Table 7*. According to the results of ANOVA for the two indicators shown in *Tables 8 and 9*, vehicle travel time was significant at the significance level of 10%, and the maximum queue length was significant at the significance level of 5%. Therefore, multiples of the safe distance significantly impacted the simulation results. As a result, it should be calibrated. Similarly, an addition to the safe distance and mean stop spacing need to be calibrated as well.

Table 6 – Simulated travel time under different parameter settings

Periods	Values of the parameter representing multiples of the safety distance				
	1	2	3	4	5
1	83.7	86.6	84.9	88.5	87.0
2	86.1	86.0	88.5	87.8	91.5
3	88.7	88.5	89.2	92.3	90.6
4	87.3	86.8	85.8	86.9	87.9
5	88.4	87.3	87.8	89.3	89.9
6	85.8	84.9	85.7	85.9	87.3

Table 7 – Simulated maximum queue lengths under different parameter settings

Periods	Values of the parameter representing multiples of the safety distance				
	1	2	3	4	5
1	134	138	137	139	139
2	141	146	145	152	153
3	137	136	139	140	142
4	136	140	138	145	144
5	142	144	145	150	152
6	132	134	138	140	144

Table 8 – ANOVA for the simulated travel time

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F	P-value	F crit
Between groups	29.171	4	7.293	2.207	0.097	2.759
Within groups	82.618	25	3.305			
Total	111.790	29				

Table 9 – ANOVA for the simulated maximum queue length

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F	P-value	F crit
Between groups	301.867	4	75.467	3.337	0.025	2.759
Within groups	565.333	25	22.613			
Total	867.200	29				

The orthogonal experimental design was used to find the optimal combination of three parameters calibrated. Five levels for each parameter were designed, as shown in *Table 10*. Therefore, the $L_{25}5^3$ orthogonal table was produced. Based on experimental results, the combination which produces the closest results to the actual situation was finally selected (coloured in bold in *Table 10*).

Table 10 – Calibrated values for the parameters

Level	An addition to the safe distance [m]	Multiples of the safe distance [m]	Mean stop spacing [m]
1	1	1	1
2	**1.5**	**2**	1.5
3	2	3	**2**
4	2.5	4	2.5
5	3	5	3

4. EFFICIENCY AND ENVIRONMENTAL IMPACTS OF CFI TRANSFORMATION

After the CFI transformation, improvements in the intersection are listed in *Table 11*.

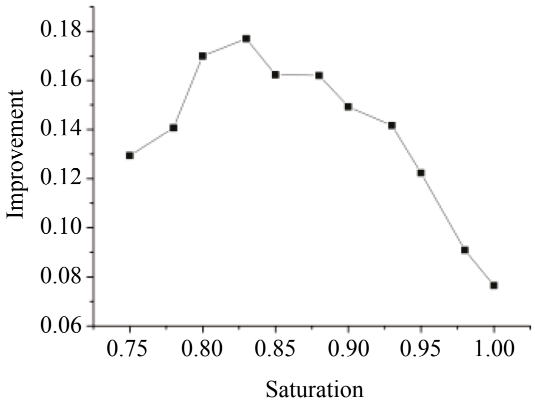
Operation efficiency: As can be seen from *Table 11*, average vehicle travel time can be reduced by 19.5%, and average vehicle delay can be reduced by 11.5%. The queue length of vehicles at the intersection can be reduced by 43.6%, and the maximum queue length can be reduced by 29.4%. The results prove that CFI transformation has a significant effect on improving the operation efficiency of intersections. The efficiency improvement will lead to the reduction of energy consumption and emissions at the intersection.

Parking rate: CFI adds an auxiliary signal control, which results in secondary parking for left-turn traffic. As a consequence, the parking rate will increase, as shown in *Table 11*. The increase in the parking rate will lead to a rise in energy consumption and emissions.

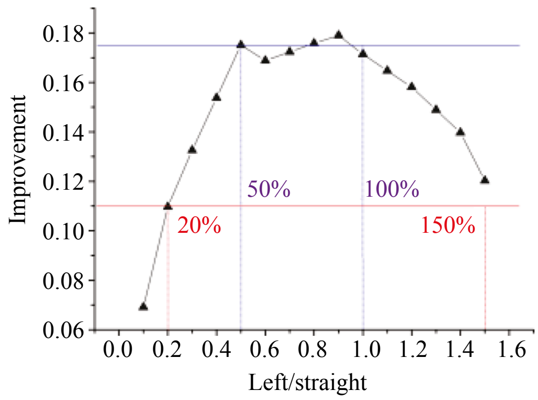
Table 11 – Improvements of the intersection after the CFI transformation

Indicator	Before CFI	After CFI	Effect
Travel time [s]	41.6	33.5	-19.5%
Delay [s]	68.7	60.8	-11.5%
Queue length [m]	39	22	-43.6%
Maximum queue length [m]	119	84	-29.4%
Parking rate	0.89	0.99	+11.2%
CO emission	1676.14	1547.99	-7.65%
NOx emission	326.12	301.18	-7.65%
VOC emission	388.5	358.76	-7.65%
Energy consumption	23.98	22.15	-7.65%

In this case study, CFI transformation will significantly reduce energy consumption and emissions. However, combining the results in operational efficiency and parking rate, it is found that the impact of CFI transformation on intersection emissions and energy consumption is not clear. It depends on the tradeoff between efficiency improvement and parking rate increase. Namely, it is related to left-turn traffic volume and through traffic volume. To enhance the sustainability of CFI transformation (efficiency improvement as well as emissions and energy consumption reduction), the optimal range for traffic flow volume, including the ratio between left-turn traffic and through traffic, needs to be clarified. We adjusted the total traffic volume while keeping ratios of flow from different directions unchanged. The emissions' improvement with the increase of left-turn traffic flow saturation is described in *Figure 9a*. As can be seen, the reduction of emissions is in a quadratic parabola relationship with traffic volume. If the traffic volume is too large or too small, the emission reduction benefit of CFI transformation cannot be guaranteed. In this case study, when the volume of left-turn traffic is close to 80%–85% of the capacity, the emission reduction benefit is obvious most. Keeping the total volume as the optimal value, we adjusted the ratios of left-turn traffic volume over through traffic volume. The simulation result was described in *Figure 9b*. With the proportion increasing, the emission reduction firstly witnesses a rising trend, then decreases. When the ratio is maintained between 50% and 100%, the reduction benefit is higher, reaching about 17%.



a) Improvement with the increase of left saturation



b) Improvement with the increase of the ratio (left-turn traffic/through traffic)

Figure 9 – The relationship between improvement concerning the emission reduction of CFI and traffic flow

5. CONCLUSION

Sustainable development of intersections, as the bottlenecks of road transportation, is critical. Focusing on intersections' reduction potential in terms of energy consumption and emissions, a traditional intersection was transformed into a CFI to fully utilise the time and space resources. After analysing the coordinated relationship between the left-turn signal at the road section and the intersection main signal, the phasing scheme of the improved CFI was designed. The VISSIM model was employed to evaluate the performance of the CFI.

The results confirmed the effectiveness of CFI from both theoretical and empirical perspectives. It can not only significantly improve the operation efficiency of intersections, but also has great potential for energy conservation and emission reduction. We only set displaced lanes at two approaches in the case study. If they are set at four approaches, the improvement in terms of energy consumption and emissions could be higher. By only adjusting the lane function without influencing the land-use area and topological form of the original intersection, CFI transformation can be widely promoted. However, it should be noted that not all intersections are suitable for CFI. To ensure the environmental benefits, factors listed in this study, such as intersection form and traffic volume, should be carefully checked. Moreover, when CFI is implemented empirically, it is suggested to do the simulation first.

The limitations of this study can be summarised as follows. Firstly, using the simulation tool, some measurement errors are inevitable. VISSIM is not specific for evaluating environmental influence. Measurements for different emissions are rough estimates. Environment-specific software (for example EnViVer) needs to be further employed to distinguish the difference in emissions. Secondly, a CFI transformation at four approaches needs to be designed to fully explore the reduction potential for energy consumption and emissions. Finally, more empirical studies are required to justify the methodology developed here and the reasonableness of CFI.

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连续流交叉口的生态效益潜力分析

摘要：

交通运输行业的节能减排对于应对全球能源和环境危机具有重要意义。交叉口作为城市道路交通的瓶颈，给城市环境带来了极大的负担。当左转交通量较大时，连续流交叉口(CFI)可以有效提高交叉口的运行效率。本文首先提出了CFI的定义和应用条件，分析了其节能减排的机理，其次以西安某典型交叉口为例进行CFI变换设计，最后利用VISSIM模型对CFI转换前后交叉口运行效率、能耗和排放进行评估。结果表明，CFI改造后交叉口的能耗和排放均大大降低。排队长度减少了41%以上。能源消耗和污染物排放减少8%左右。通过仿真分析，当左转交通量为设计通行能力的80% ~ 85%，且左转交通量占总交通量的比例维持在50% ~ 100%时，减排效果最佳。本研究结果表明，在经过仔细检验的情况下CFI适合进行大规模推广。

关键词：

可持续交通；交叉口设计；连续流交叉口；效率提升; VISSIM仿真