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A NOVEL MULTIMODAL TRANSPORT MODEL FOR SCHOOL COMMUTING

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During peak hours, the roads surrounding schools often become a source of concern due to severe traffic congestion. This not only leads to a substantial increase in travel time but also poses heightened safety risks. This study proposes a multimodal transport model that integrates private cars, shared parking spaces, and school buses (CPB) to address these challenges. The model aims to improve traffic efficiency and reduce safety hazards. The approach involves two key phases: identifying optimal locations for private car parking and optimizing school bus routes. Results show an 18.53% reduction in private car costs and an 8.13% decrease in traffic delays within the road network. The advantages of this model become particularly significant when student commuting demand exceeds 70% of peak transportation demand. This study provides a robust scientific foundation for developing traffic management strategies around schools.

Keywords: Urban Traffic Management; School Commuting; Shared Parking; Path Optimization.

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1. INTRODUCTION

School commuting is a significant contributor to urban congestion and a major cause of road injuries among children. In China, an average of 10 children lose their lives, and 53 are injured daily in road traffic accidents (World Health Organization, 2023). According to China's road traffic safety laws, individuals must be at least 12 years old to operate a bicycle or tricycle and at least 16 years old to ride an electric bicycle. As a result, school travel for primary and secondary students largely depends on motor vehicles.

During peak hours, school-related travel accounts for 5%–7% of vehicle miles traveled and 10%–14% of all private vehicles on the road (McDonald *et al*., 2011). The high concentration of vehicles around schools significantly increases the risk of traffic congestion and safety hazards. The situation is further aggravated by vehicles moving at low speeds in search of parking spaces and engaging in random parking behavior (Rothman *et al*., 2017).

Influenced by the age of students (Rafiq and Mitra, 2020) and distance traveled (Li *et al*., 2015; Smith *et al*., 2024), school buses and private cars are the primary mode of travel (Tupper *et al*., 2024, Qian and Melachrinoudis, 2024). Research shows: An efficient school bus routing system can significantly reduce transportation time and costs while ensuring the safety and comfort of students (Qian and Melachrinoudis, 2024). Furthermore, using public transportation, such as school buses, is more conducive to sustainable development (Cakmak *et al*., 2023).

However, school bus travel has limitations, including reduced flexibility and the additional costs of walking, waiting, and detouring (Malodia and Singla, 2016). Challenges also persist in bus stop selection, route generation, scheduling, and strategic transportation policies (Ellegood *et al*., 2020). On the other hand, private car travel has become the most popular commuting mode due to its comfort, flexibility, and minimal walking distances (Mandic *et al*., 2024), especially with the rapid rise in vehicle ownership (Wang and Ma, 2024). Nonetheless, this mode consumes a significant amount of road resources. The large concentration of private cars around schools not only leads to traffic congestion but also severely impacts the capacity of the urban road network.

Another contributing factor to frequent road congestion around schools is the inadequacy of infrastructure, such as parking spaces (Zhang *et al*., 2017). Research indicates that over 80% of roads surrounding schools lack essential infrastructure, such as designated parking zones and sidewalks (Ali *et al*., 2023). Due to constraints on road space, the development of additional infrastructure is often challenging (Sasai *et al*., 2024, Loop *et al*., 2016).

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Shared infrastructure offers a potential solution by improving the utilization of existing road resources. This approach has garnered significant attention from researchers (Liu *et al*., 2021; Zhang *et al*., 2024; Gu *et al*., 2024). Studies have demonstrated that shared traffic facilities can effectively reduce congestion associated with school and work travel (Li *et al*., 2024). The concept of sharing has also been widely applied to other domains, including charging facilities (Zhang *et al*., 2024), carriers (Liu *et al*., 2024), and logistics platforms (Radhi, 2024).

Currently, traffic management strategies for roads around schools primarily focus on regulating traffic flow. One approach aims to reduce the demand for private car commuting by supporting school bus services through competitive funding and legislative measures (Prasad and Maitra, 2019; Steffen *et al*., 2024). Another approach focuses on minimizing traffic disruptions by regulating vehicle behavior. For example, Reyad *et al*. (2017) identified traffic violations as a major cause of congestion and safety risks around schools. Similarly, Li *et al*. (2021) utilized automated vehicle recognition technology to analyze vehicle behavior and proposed countermeasures to address congestion. Hu *et al*. (2024) demonstrated that regulating parking behavior and imposing speed limits can effectively mitigate congestion and safety hazards near schools.

While these studies can enhance the operational efficiency of school roads, they are often constrained to a single transport mode. They overlook the potential of intermodal systems that integrate private cars, school buses, and other modes. This limitation not only fails to address the inherent shortcomings of individual modes but also prevents the full utilization of their combined advantages. Additionally, traffic flow regulation faces practical challenges due to constraints on educational and road resources, as well as the variability of traffic conditions across different schools.

To address these challenges, this study proposes a CPB (Private Car–Shared Parking Space–School Bus) intermodal transport model. This approach integrates private cars and school buses during peak school hours while leveraging shared on-street parking resources. The goal is to optimize the allocation of parking resources without requiring significant investments in new infrastructure. In this model, students are dropped off at designated locations by private cars and then transported to school by school buses. The objective is to develop a transportation solution that balances efficiency and flexibility, reduces reliance on private cars, and enhances the efficiency of school-area road networks.

The structure of this paper is as follows: First, it introduces the research question. Second, it explains the methodology and details the proposed model. Third, it analyzes the study's results. Subsequently, it discusses the findings in the context of existing literature. Finally, the paper concludes with a summary of key insights and implications.

2. PROBLEM STATEMENT

This study proposes the CPB transport mode, which focuses on the efficiency of student transfers and road network traffic. In the subsequent sections, we will analyze the advantages and applicability of the mode.

The model is briefly described as follows: To accommodate the parking needs of escort private cars, a temporary parking zone is designated along a lane within a specified vicinity of the school area. This zone includes separate areas for both escort private car parking and school bus parking. The school bus parking area is located at the front end of the road parking zone, where vehicles are parked in parallel. Upon the arrival of an escort private car, a temporary berth is made available, and students are simultaneously transported by the school bus to this location. Students then transfer from the school bus to the waiting escort private car to continue their travel. It is assumed that these temporary on-street parking zones are exclusively reserved for escort private vehicles during specific parking periods, such as school rush hours, and are not accessible to regular vehicles.

This paper focuses on a primary school commuting network that extends outward from the school center. The boundary of this region is determined by the availability of potential road parking resources. This network, denoted as $H = (J, A)$ comprises a set J of nodes and a set A of links. Nodes in the network include the school itself and entrance/exit points at the edges of the regional area. Entrances are designated as traffic origins O for parents, while exits serve as traffic destinations D for parents. It's possible for a node to function as both an entrance and an exit. Links within the network consist of regular road segments and parking road sections equipped with on-street parking zones.

The components of each link in the network include the number of lanes, lane width, capacity, and length. Factors influencing the road traffic supply level are also considered, such as road section design, support for slow traffic systems (ensuring remaining traffic capacity after implementing parking zones, ensuring safe student transfers, and providing transfer spaces), speed limits, signal intersection density, signal control, density of bus stops, presence of non-motor vehicles, and availability of public parking lots in the school district. Figure 1 illustrates an example network within the school district showcasing the CPB mode. The blue circle in the figure represents the selected parking section, where the escort private vehicles transport students to the location, and then the school bus escorts them to the school.

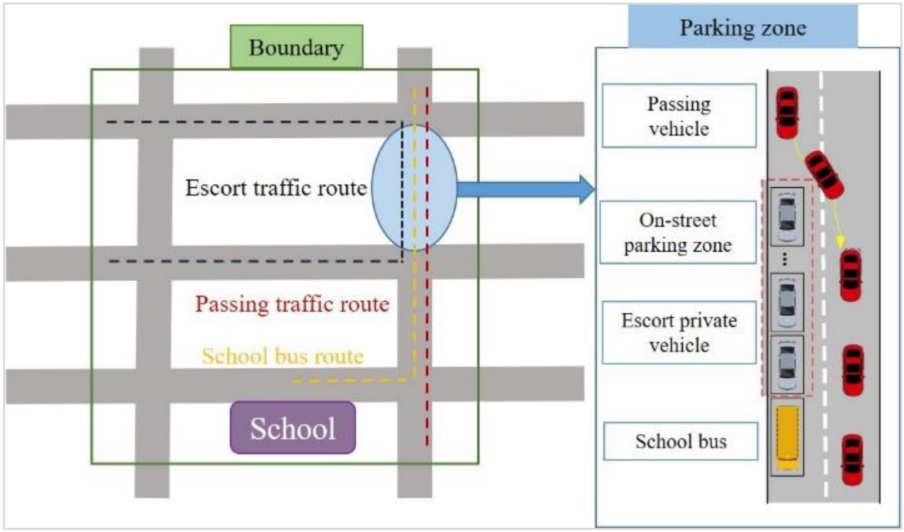

Figure 1. Network diagram of CPB mode

The CPB mode involves key stakeholders such as governments, parents, children, school administrators and school bus operators. Parents typically travel from workplace/home/other parking zone-workplace/home/other using private cars throughout their travel.

Students follow a trip chain of "school-parking zone-workplace/home/other". They initially commute by school bus and then transfer to a private car for the second leg of their travel. Our focus remains within the network region due to the diverse origins of parents and the destinations of students during school hours.

This paper aims to optimize parking resources around the school and develop transportation plans by focusing on the costs incurred by each stakeholder in accomplishing their objectives during school trips, particularly examining time costs.

3. METHODS

This study assumes that the road traffic flow consists exclusively of motor vehicles and does not include non-motor vehicles. Our analysis focuses solely on vehicles within the network region. The time cost of travel for various stakeholders is measured from the perspective of these vehicles. The traffic demand generated by the school commuting network region can be categorized into passing traffic and escort traffic, which includes escort private cars and school buses. For individual travel costs, the cost associated with escort private cars represents the travel expenses for parents. Student travel costs are influenced by the operational times of escort private cars, the driving and stopping durations of school buses, and waiting times. This section examines the time costs of escorting private cars T^{escort}, passing vehicle costs T^{pass}, and school buses T^{bus} based on the operational processes and conditions of these vehicles. Specific calculations of travel costs are shown in Appendix A.

To optimize school transportation organization, addressing the assignment of escorting private cars to parking sections and solving the school bus routing problem are essential. This study does not consider the path selection behavior of passing traffic flow influenced by on-street parking, thus excluding traffic assignment. Consequently, it can be viewed as a location-routing problem within a specific scenario, with optimization theory applied for modeling.

3.1 Parameters

The parameters and decision variables in the mathematical model are listed in Table 1.

Table 1. The parameters and decision variables in the mathematical model

Parameter	Meaning
I	Set of escort private cars
M	Set of school buses
0	School
T_{i0a}^{car-in}	The travel time of the escort private cars $i$from the origin O to the parking zone of section a

$T_{iaD}^{car-out}$	The travel time of the escort private cars $i$from the parking zone of section a to destination D
$T_{a}^{car-wait}$	Waiting time for all escort private cars in the parking zone of section a
$T_{a}^{car-queue}$	Queuing time for all escort private cars in the parking zone of section a
$T_{maa'}^{bus-drive}$	The travel time of the school bus m from section a to section a'
$T_{ma}^{bus-wait}$	Dwell time of school bus m at the parking section$a$
n_{ma}	The number of students served by school bus m at the parking section$a$
Q_m	Capacity of school bus$m$
N_a	Number of parking spaces assigned for section a
N_p	Total number of escort private cars
$N_{a,min}$	The Minimum number of parking spaces in section a
$N_{a,max}$	The maximum number of parking spaces in section a
l_{ma}	Number of students on school bus$m$after service the parking section$a$
Z_{ma}	The time when school bus m arrives at the parking section$a$
z_{ia}	If the escort private cars i parked in section a is late, $z_{ia}=1$, otherwise 0
Decision variable	Meaning
x_{ia}	If the escort private cars i parks at section a, $x_{ia}=1$, otherwise 0
$y_{maa'}$	If the school bus m continues to serve section a after serving section a',$y_{maa'}=1$, otherwise 0

3.2 Objective Functions and Constraints

The travel costs related to transportation include the travel time costs for escort private cars (EC), passing vehicles (PC), and school buses (BC).

The travel time cost of the escort private cars (EC) is shown in equation (1).

$$EC=\sum_{a\in A}\sum_{i\in I}\sum_{O\in N}x_{ia}T_{iOa}^{car-in}+\sum_{a\in A}\sum_{i\in I}\sum_{D\in N}x_{ia}(1-z_{ia})T_{iaD}^{car-out}+\sum_{a\in A}\left(T_{a}^{car-wait}+T_{a}^{car-queue}\right)+\sum_{a\in A}\left(T_{a}^{punish-early}+T_{a}^{punish-late}\right)+\sum_{a\in A}\sum_{i\in I}\sum_{D\in N}x_{ia}z_{ia}\left(T_{ia0}^{car-in}+T_{i0D}^{car-out}\right) \tag{1}$$

The travel time cost of the passing vehicle (PC) is shown in equation (2).

$$PC=\sum_{a\in A}x_{ia}T_{a}^{psss} \tag{2}$$

School bus travel time cost (BC) is shown in equation (3).

$$BC=\sum_{m\in M}\sum_{a\in A}\sum_{a'\in A}T_{maa'}^{bus-drive}y_{maa'}+\sum_{m\in M}\sum_{a\in A}\sum_{a'\in A}T_{ma'}^{bus-wait}y_{maa'} \tag{3}$$

Our objective is to minimize the total travel time cost of traffic flow in the network, while accounting for transfer efficiency and network traffic efficiency. The model is structured as follows:

$$min\,T\,C=EC+PC+BC \tag{4}$$

Subject to:

$$\sum_{a\in A}x_{ia}=1\,,\forall i\in I \tag{5}$$

$$\sum_{m\in M}\sum_{a\in A}y_{maa'}=1,\forall a'\in A \tag{6}$$

$$l_{ma}-n_{ma}-l_{ma'}\le\xi_1(1-y_{maa'}),\forall a\in A,\forall a'\in A \tag{7}$$

$$Z_{ma}+T_{maa'}^{bus-drive}+T_{ma'}^{bus-wait}-Z_{ma'}\le\xi_2(1-y_{maa'}) \tag{8}$$

$$l_{m0} \leq Q_m \tag{9}$$

$$\sum_{m\in M}\sum_{a\in A} y_{mal} - \sum_{m\in M}\sum_{a\in A} y_{mla'} = 0, \forall l \in A \tag{10}$$

$$Z_{ma} \leq T_{max} \tag{11}$$

$$Na_{a,max}{}_{a,min} \tag{12}$$

$$\sum_{a\in A} N_a = N_p \tag{13}$$

$$N_a = \sum_{i\in I} x_{ia}, \forall i \in I \tag{14}$$

$$\frac{V_a}{C_a} \leq b_0 \tag{15}$$

Equation (5) stipulates that each escort private car must select exactly one parking road section. Equation (6) mandates that each parking zone must be visited by a school bus exactly once. Equation (7) denotes the change in the number of bus loads at consecutive parking zones along the bus route. To linearize the nonlinear inequality, a sufficiently large positive integer ξ_1 is introduced. Equation (8) defines the relationship between the travel times of consecutive stations in the school bus route, where ξ_2 serves a similar purpose as ξ_1 in linearization. Equation (9) sets the school bus capacity limit. Equation (10) requires the school bus to depart after visiting a parking section. Equation (11) ensures that the travel time for students does not exceed the maximum allowable travel time T_{max}. Equations (12) and (13) specify limits on the number of available parking spaces. Equation (14) describes the supply and demand balance for the number of parking spaces. Equation (15) imposes a road service level constraint.

3.3 Solution Methods

To solve the problems of selecting parking sections for each escort private car and optimizing school bus routing, we can approach it in two stages:

In the first stage, the optimization objective is to determine the parking section selected by each escort private car while minimizing the total cost. Each parent's choice of parking section and the number of students picked up at each section are computed under the constraint of minimizing total cost. Due to capacity limitations at parking sections, ensuring fairness in parental choices is not considered here. Instead, the system's overall efficiency is prioritized, treating this as an assignment problem. The escort private car's parking section selection process is akin to a specialized distribution center location problem, which is tackled using a genetic algorithm.

In the second stage, the goal is to optimize the school bus route under the optimal cost obtained from the first stage. This involves solving the vehicle path optimization problem for the school bus route. An ant colony algorithm is chosen to find the optimal school bus route.

These two stages collectively address the challenges of parking section assignment for escort private cars and the efficient routing of school buses, optimizing overall transportation logistics for the school system. The process of the solution algorithm is shown in Figure 2.

4. RESULTS

4.1 Case Description

To illustrate the effectiveness of our approach, we conducted a case study at a school in Changchun, China. Based on our survey findings: The demand for escort private cars during school hours is 510. Origin-destination (OD) data for escort private cars is collected through surveys. Around the school, there are 28 alternative parking sections available within the selected commuting network. Figure 3 displays the locations of the network entrance and exit OD points, as well as the alternative parking sections.

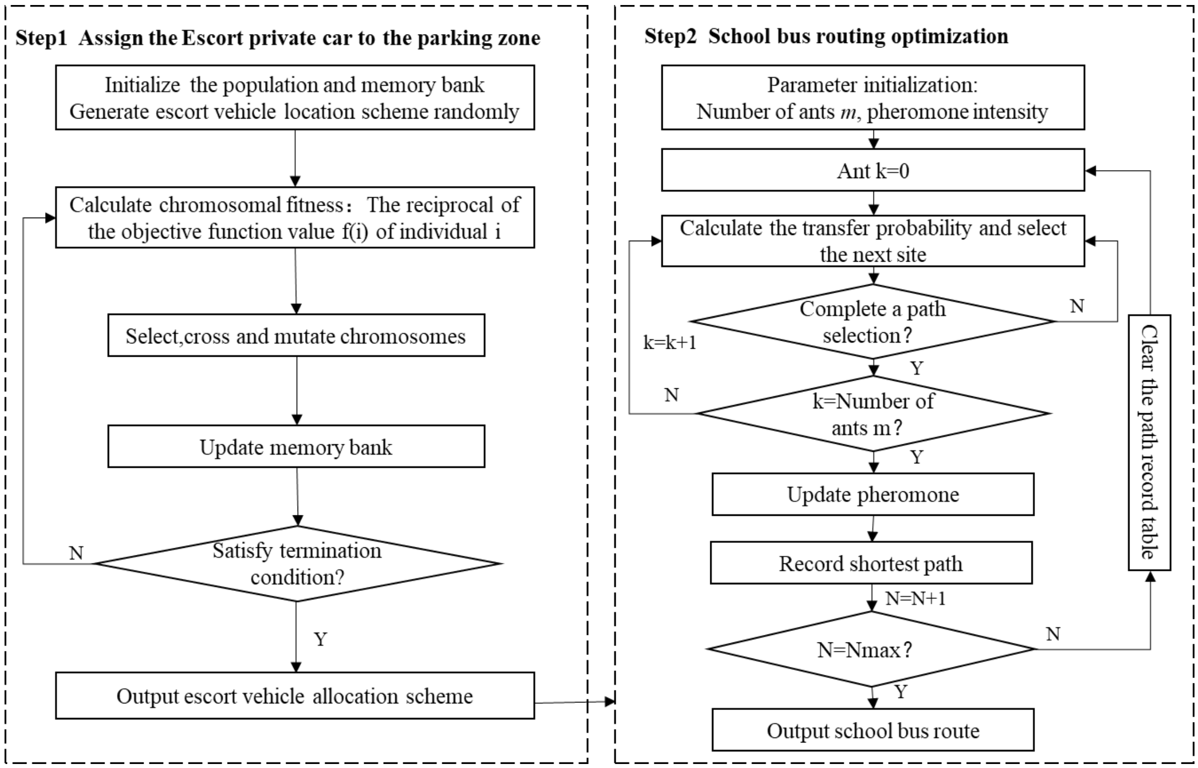

Figure 2. The process of the solution algorithm

The time window Δt^{a} of the parking section a is shown in equation (16).

$$\Delta t^{a} = G(N_a) = \frac{1}{5}N_a + 8, N_a \in [10, N_{a,max}[]] \quad (16)$$

The probability density function for the arrival of escort private cars is shown in equation (17).

$$r_a(t) = \frac{e^{-\left(t-(t_1^{a}+\Delta t^{a})\right)/2.73}}{2.73\left[1+e^{-\left(t-(t_1^{a}+\Delta t^{a})\right)/2.73}\right]^2} \quad (17)$$

The passing vehicle delay is influenced by parameters such as traffic flow speed, flow rate, and density. Therefore, it is essential to construct both a speed-flow model and a speed-density model.

The relationship between speed and flow is determined based on the BPR model, as shown in equation (18).

$$v = \frac{v_0}{\left[1+\alpha\left(\frac{q}{C}\right)^{\beta}\right]} \quad (18)$$

where v_0 is free flow speed, q is traffic flow, and C is capacity, α and$\beta$are the corresponding parameters.

Due to the reduction of lane number and the change of lateral clearance in the lane reduction area, the road traffic capacity after setting the on-street parking is $C' = C_0 * \gamma * \eta$. Where C_0 is the traffic capacity of the road before on-street parking, γ is the reduction factor of the number of remaining lanes, and η is the reduction factor of lane width and lateral clearance.

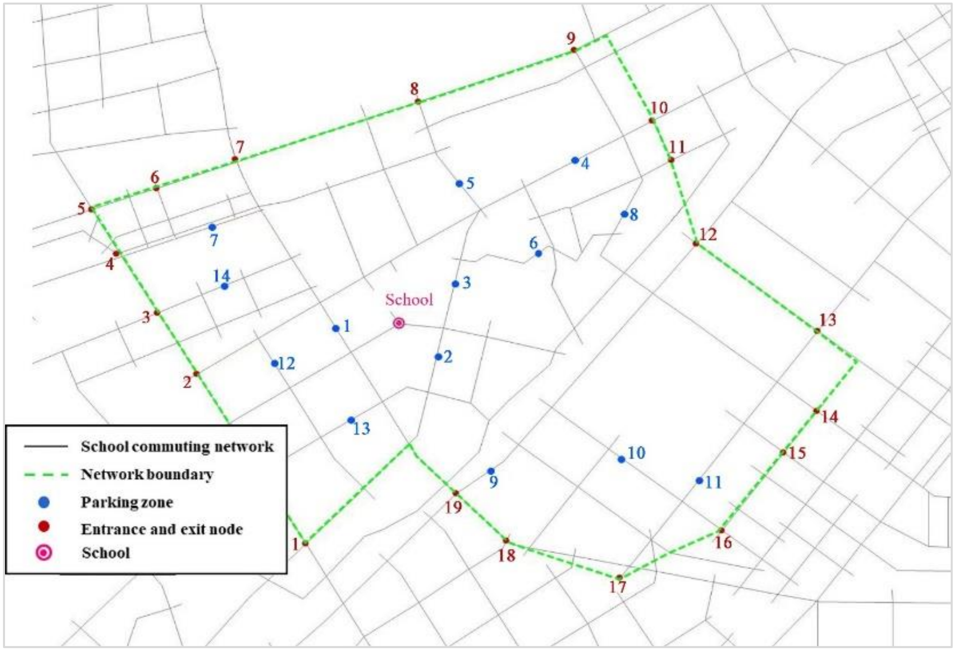

Figure 3. The locations of network entrance and exit OD and alternative parking sections

Speed-density relationship model is shown in equation (19-21).

$$v_{out} = \frac{1}{2}\left[14.204 \times ln\left(\frac{216.412}{k_{out}}\right) + 7.169 \times ln\left(\frac{254.497}{k_{out}}\right)\right] \quad (19)$$

$$v_{in} = \frac{1}{2}\left[69.647 \times e^{-\frac{k_{in}}{14.449}} + 12.716 + 51.08 \times e^{-\frac{k_{in}}{100.1}} - 22.45\right] \quad (20)$$

$$k = k_{out} + k_{in} \quad (21)$$

where v_{out} is outer lane speed, v_{in} is inner lane speed, k_{out} is outer lane density, k_{in} is inner lane density, k is road section density.

The width of the parking space is standardized at 2 meters. Additional relevant parameters are detailed in Table 2.

Table 2. Related information.

Parameter	Unit	Numerical value	Parameter	Unit	Numerical value
v^{walk}	$m \cdot s^{-2}$	1	L_s	m	5
t^{in}	s	10	α_1	/	0.803
a_d	$m \cdot s^{-2}$	-2.5	β_1	/	2.418
a_h	$m \cdot s^{-2}$	2	b_0	/	1
t_c	s	7	Q	seats	52
t_w	s	4	T_{max}	s	1200

4.2 Result Analysis

MATLAB R2021a programming was employed to solve the problem using a genetic algorithm. The results obtained are as follows: The total cost function for escort private cars was calculated as 301.61 hours. The total cost for passing vehicles amounted to 1154.48 hours. The total cost for school buses was determined as 204 minutes.

Detailed results can be found in Table 3. The school bus route solution, based on the number of escort private cars at each parking zone, is presented in Table 4. Additionally, the school bus route is illustrated in Figure 4.

Table 6 presents various costs and comparative data between the private car and CPB modes. The CPB mode shows a reduction in total costs by 10.28% compared to the private car mode. In the private car mode, the average travel time for parents is 43.56 minutes, whereas in the CPB mode, it decreases to 35.48 minutes, marking an 18.53% reduction. Specifically, waiting time and queuing time for escort private cars decreased by 61.05% and 71.56%, respectively, and traffic delays in the school commuting network region decreased by 8.13%.

These findings indicate that the CPB mode effectively addresses traffic congestion around the school, significantly reducing parent waiting and queuing times.

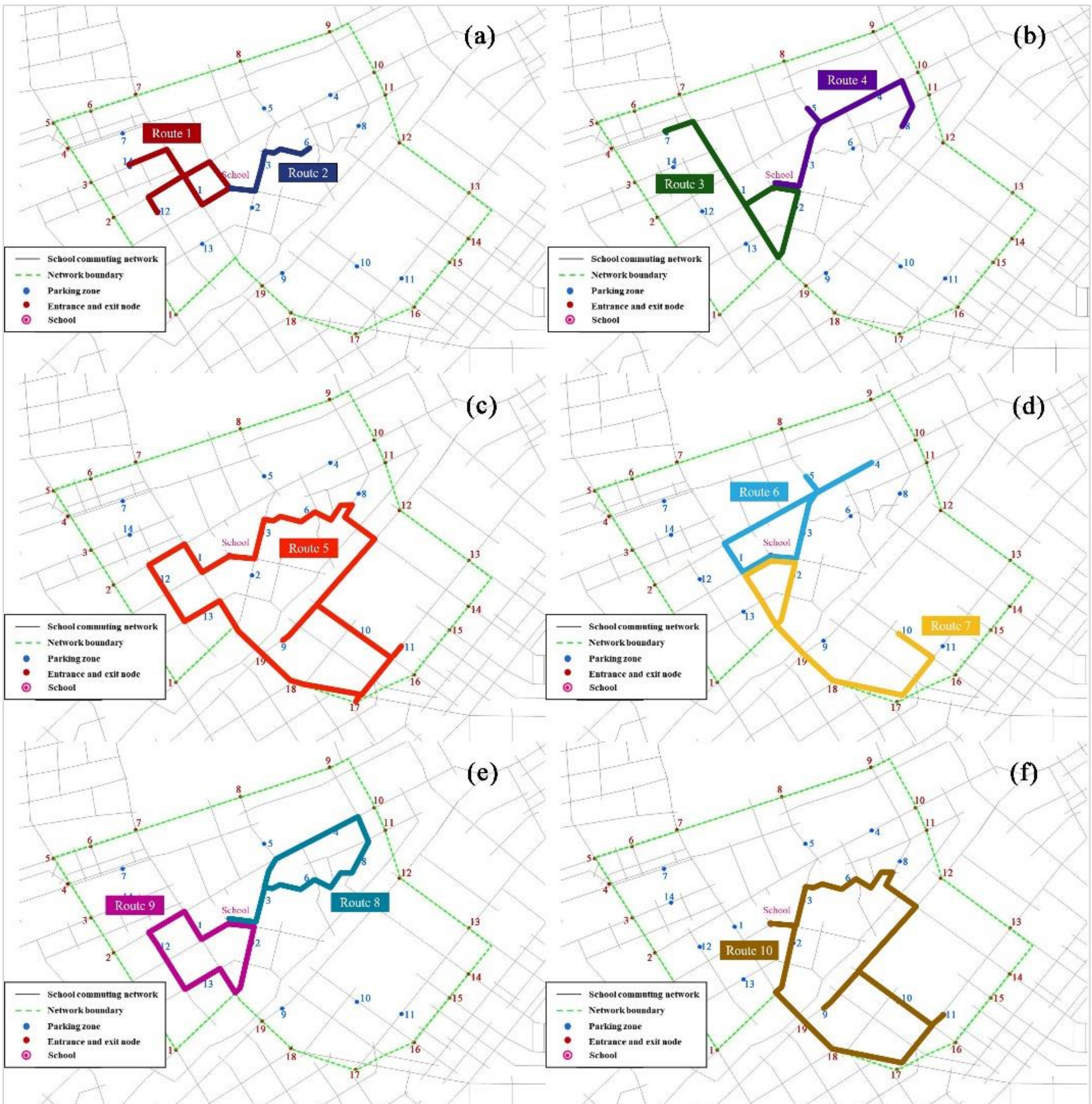

Figure 4. School bus routes. (a) Routes 1 and 2. (b) Routes 3 and 4. (c) Route 5. (d) Routes 6 and 7. (e) Routes 8 and 9. (f) Route 10

Table 3. The number of escort private cars at the parking zone

Parking zone number	Number of students (unit)	Parking zone number	Number of students (unit)
1-1	11	8-1	13
1-2	20	8-2	16
2-1	14	9-1	18
2-2	25	9-2	16
3-1	17	10-1	25
3-2	20	10-2	16
4-1	14	11-1	20
4-2	16	11-2	14
5-1	17	12-1	16
5-2	17	12-2	26
6-1	18	13-1	24
6-2	32	13-2	21
7-1	21	14-1	16
7-2	17	14-2	10

Table 4. School bus route

School bus	Students per bus	Route	Travel time (min)
1	52	School- (14-1) - (14-2) - (12-2) -School	18
2	52	School- (3-2) - (6-2) -School	7
3	49	School- (1-1) - (7-1) - (7-2) -School	17
4	46	School- (5-2) - (4-2) - (8-1) -School	20
5	53	School- (13-2) - (11-2) - (9-1) -School	29
6	51	School- (1-2) - (5-1) - (4-1) -School	13
7	50	School- (2-2) - (10-1) -School	20
8	51	School- (3-1) - (6-1) - (8-2) -School	14
10	54	School- (12-1) - (13-1) - (2-1) -School	13
9	52	School- (9-2) - (10-2) -(11-1) -School	23

Table 5. Travel cost analysis of various modes

Analysis Index	Private Car Mode (hour)	CPB Mode (hour)	Comparison
Driving	110.48	96.28	12.85%
Waiting	103.86	40.45	61.05%
Queuing	28.2	8.02	71.56%
Departure	127.68	108.62	14.93%
Delay	1256.58	1154.48	8.13%
Total	1626.8	1459.49	10.28%

4.3 Sensitivity Analysis

In this section, we focus on identifying the key factors influencing system costs through sensitivity analysis and examine their impact on both CPB mode and Escort Private Car Mode (CM). The model's applicability is explored by analyzing how variations in passing traffic demand affect the proportion of pick-up traffic in the road network, keeping pick-up demand constant.

Figure 6 illustrates the findings. As passing traffic demand increases, both the costs of Escort Private Car Mode and CPB mode escalate, with Escort Private Car Mode showing a sharper increase. When demand changes are less than 70%, Escort Private Car Mode outperforms CPB mode. However, as demand changes exceed 70%, CPB mode becomes superior, with its advantage becoming increasingly evident. Notably, CPB mode exhibits greater resilience to traffic fluctuations compared to Escort Private Car Mode.

As depicted in Figure 7, the increase in passing traffic demand primarily contributes to the network's travel costs, predominantly due to traffic delays of passing vehicles. This factor is less influenced by pick-up demand fluctuations. Additionally, in CPB mode, the pick-up costs of escort private cars increase at a slower rate compared to other factors.

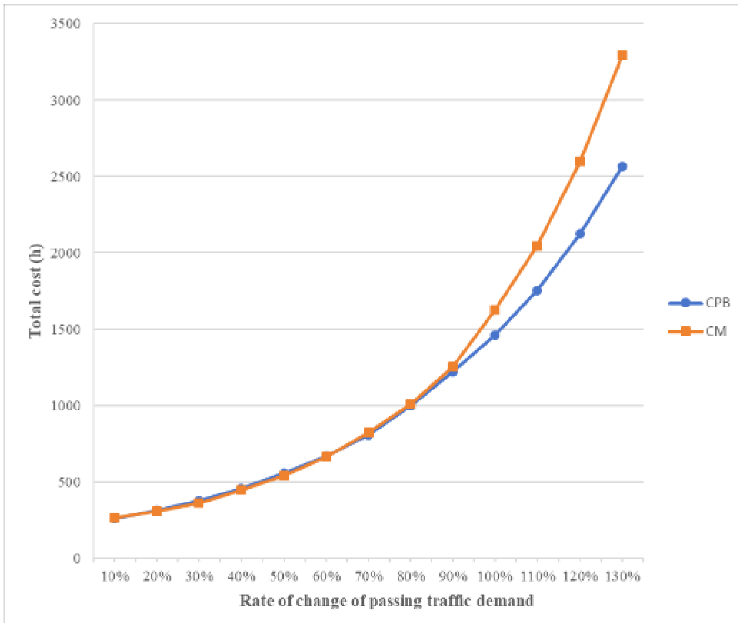

Figure 6. Total cost variations with passing traffic demand

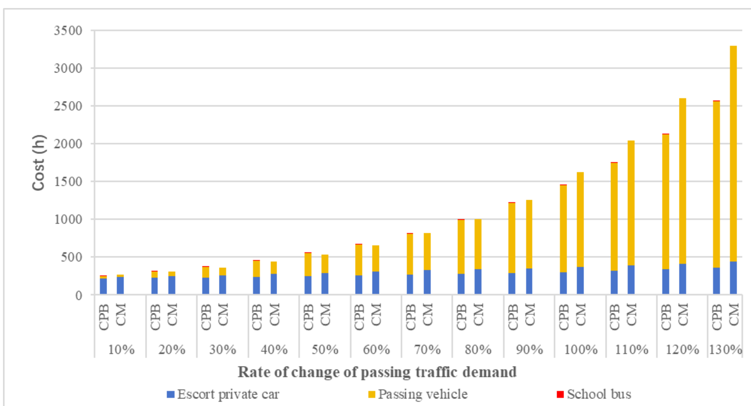

Figure 7. Various cost variations with passing traffic demand

5. DISCUSSIONS

This study proposes an intermodal transport model (CPB) that integrates private cars and school buses for through-school travel based on the concept of shared parking. The model aims to enhance traffic efficiency within the road networks surrounding schools. First, the CPB travel process is analyzed using the school road network as a foundation for cost calculation. Second, the travel costs associated with escorting private cars, school buses, and passing vehicles are computed. Then, an optimization model is developed with the objective of minimizing the total travel time. Finally, the problem is addressed using genetic algorithms and ant colony algorithms. This study contributes to alleviating urban traffic congestion and advancing sustainable development by:

(1) Enhance the traffic efficiency of the urban road network

The CPB mode enhances the traffic efficiency of road networks by integrating two transport modes—private cars and school buses—to facilitate through-school travel. This approach effectively mitigates the inefficiencies of private cars consuming excessive resources and school buses being less flexible. School bus transfer points are strategically located in areas with enough traffic resources, ensuring that school travel efficiency improves without imposing additional burdens on the road network. The results demonstrate that the CPB mode reduces through-school travel time by 18.53%, decreases traffic delays by 8.13%, and improves road network operational efficiency by 10.28%, as shown in Table 6.

Current studies on urban traffic networks primarily focus on congestion level prediction (Zheng *et al*., 2024), vehicle path planning (Xing and Li, 2023), and traffic flow regulation (Zhou *et al*., 2022). While these measures can enhance traffic efficiency, they often fail to adapt to the dynamically changing of traffic conditions, limiting their applicability across diverse scenarios.

Guiding urban development through public transportation is recognized as an effective means of improving traffic efficiency (Wang and Loo, 2024). However, issues such as limited flexibility and long walking distances often hinder its widespread adoption (Malodia and Singla, 2016). In contrast, the high flexibility of private cars and non-motorized vehicles can effectively address the limitations of public transport.

Thus, leveraging the efficient use of traffic resources through the combined transport of multiple modes presents a promising new approach to urban traffic management. This integration offers a balanced solution that optimizes both efficiency and flexibility, paving the way for more sustainable urban transportation systems.

Table 6. The Comparison of private car mode and CPB mode

Traffic	Analysis Index	Private Car Mode (h)	CPB Mode (h)	Comparison
School bus	Driving time	/	2.90	/
	Waiting time	/	0.50	/
	Subtotal	/	3.40	/
Escort private car	Driving time	110.48	96.28	12.85%
	Waiting time	103.86	40.45	61.05%
	Queuing time	28.20	8.02	71.56%
	Departure time	127.68	108.62	14.93%
	Early arrival punishment time	/	12.75	/
	Late arrival punishment time	/	35.49	/
	Subtotal	370.22	301.61	18.53%
Passing vehicle	Deceleration delay	/	0.50	/
	Merging delay	/	1153.18	/
	Low-speed driving delay in the reduced area	/	0.02	/
	Acceleration departure delay	/	0.78	/
	Subtotal	1256.58	1154.48	8.13%
All	Total	1626.80	1459.49	10.28%

(2) Reduce traffic congestion on roads around schools

The primary cause of traffic congestion in school areas is frequent parking and the large concentration of pick-up and drop-off vehicles (Liu *et al*., 2024). To address this issue, this study disperses the escort of private cars to neighboring areas and uses buses to transport students to school. This approach minimizes disruptions to traffic efficiency caused by vehicle parking and related behaviors. The results demonstrate a total reduction of 116.85 hours in travel time for escort private cars and 102.1 hours in travel time for passing vehicles, as shown in Table 6.

Existing research on traffic management around schools has largely focused on regulating driving behavior (Hu *et al*., 2024) and managing traffic flow (Eun, 2023). However, these efforts primarily target passing vehicles. During school commuting periods, the traffic flow generated by schools is relatively fixed, and solely managing passing vehicles does not fundamentally resolve the congestion issues.

(3) Balance of supply and demand under transport resource constraints

Schools are often located in urban residential areas, where expanding roads and creating additional parking spaces is highly challenging. However, school commuting generates a significant demand for vehicle parking, which the existing infrastructure fails to meet. This imbalance not only increases the low-speed driving time and the frequency of acceleration/deceleration but also leads to random and disorderly parking.

To address this issue, this study leverages the concept of sharing by utilizing vacant parking spaces in areas near schools. The findings demonstrate that in the CPB mode, the delay time caused by low-speed driving is reduced to only 0.2 hours, while the delay time caused by acceleration and deceleration is reduced to 1.28 hours, as shown in Table 6. Previous studies have paid limited attention to this specific issue, with most efforts focusing on alleviating the parking supply-demand imbalance by promoting public transportation options such as school buses (Feng *et al*., 2023).

6. CONCLUSIONS

Based on the concept of parking sharing, a shuttle transportation mode combining private cars and school buses is proposed to alleviate school traffic congestion during commuting hours. The CPB model aims to optimize the allocation of transportation resources and improve commute organization. Numerical examples and sensitivity analysis validate the feasibility of the model, yielding the following results:

Compared to the private car mode, the CPB mode reduces overall travel costs, achieving a total cost reduction of 10.28%. Specifically, escort private car costs decrease by 18.53%, while waiting and queuing times are reduced by 61.05% and 71.56%, respectively. Intermodal transportation not only reduces the wait times but also minimizes detours. This results in a 23.36% reduction in school commute driving time and a 7.44% reduction in work/home stage driving time. Traffic delays within the school road network are also reduced by 8.13%. Sensitivity analysis indicates that the CPB mode is most effective when passing traffic exceeds 70% of peak demand. These findings suggest that the CPB mode effectively addresses traffic congestion near schools, significantly reducing wait and queue times for escort private cars while enhancing overall transportation efficiency.

This paper presents an initial exploration of the intermodal transportation mode combining private cars, shared parking spaces, and school buses, which has yet to be implemented in practice. It acknowledges several limitations: The scenario is simplified and overlooks the varying traffic conditions across the road network. Additionally, the model construction does not account for scheduling issues in the temporal dimension. Future research could incorporate time-varying traffic patterns, uncertainties in demand scale, parental compliance rates, and flexibility in scheduling time windows. Currently, the model focuses solely on vehicle costs as the primary target for optimization. Future iterations could include other cost factors, such as student travel expenses, vehicle maintenance costs, and security expenses. Addressing these aspects in future research would enhance the applicability and robustness of the proposed intermodal transportation mode in real-world settings.

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APPENDIX A –Travel Cost

A.1 Escort Private Cars

Parents will drive escort private cars along the normal road sections, entering the school area from the traffic origin *O* and proceeding to the designated parking road section. Within the specified time $[t_1^a, t_1^a + \Delta t^a]$, all escort private cars will sequentially park in the on-street parking zone upon arrival, waiting for the school bus to arrive. The school bus arrives at time $t_1^a + \Delta t^a$ and disembarks students at time $[t_1^a + \Delta t^a, t_2^a]$. During this time $[t_2^a, t_3^a]$, all parents queue to pick up their students. Parents and students walk to their cars, board them, and depart in order. Finally, they exit at the traffic destination *D* on the network edge. Note that this scenario does not consider trip generations and attractions within the network.

The time cost of escort private cars T^{escort} includes: driving time T_{Oa}^{car-in} from origin *O* to parking section *a*, waiting time $T_a^{car-wait}$, queuing time $T_a^{car-queue}$, and departure time $T_{aD}^{car-out}$ from parking section *a* to destination *D*. In addition, if the vehicle does not arrive at the parking position within the stipulated time, additional punishment costs T_a^{punish} are added.

Waiting Time

The time window Δt^a of road section a is influenced by the number of parking spaces N_a and adheres to the formula $\Delta t^a = G(N_a)$.

Suppose the arrival probability density function of escort private cars is $r_a(t)$, determined through fitting survey observation data and satisfying formula $\int_{-\infty}^{+\infty} r_a(t)dt = 1$.

It is assumed that all vehicle arrivals follow a specific function and are not influenced by road traffic flow. Escort private cars arrive and park sequentially. The waiting time for all vehicles that arrive (i.e., arrive on time) within the time $[t_1^a, t_1^a + \Delta t^a]$ is shown in equation (A.1).

$$T_a^{car-wait} = \int_{t_1^a}^{t_1^a+\Delta t^a} [(t_1^a + \Delta t^a - t)N_a r_a(t)]dt \tag{A.1}$$

Punishment Time

The failure of escort private cars to arrive at the parking zone within the specified time window is categorized into two cases: early arrival and late arrival. The proportion of early arrival, punctual arrival, and late arrival is related to parameters $r_a(t)$ and Δt^a.

When a vehicle arrives early, i.e., at time $\left[-\infty, t_1^a\right]$, its dwell time on the road network increases. Therefore, the waiting time for an early arrival vehicle is shown in equation (A.2).

$$T_a^{punish-early} = \int_{-\infty}^{t_1^a}[(t_1^a - t)N_a r_a(t)]dt + \Delta t^a \int_{-\infty}^{t_1^a}[N_a r_a(t)]dt \tag{A.2}$$

When a vehicle arrives late, i.e., at time $[t_1^a + \Delta t^a, -\infty]$, it must proceed to the school and wait for the school bus serving this area to return to the school at time t_4^a to pick up the student. Subsequently, it drives to destination *D*. Therefore, the waiting time for late arriving vehicles is shown in equation (A.3).

$$T_a^{punish-late} = \int_{t_1^a+\Delta t^a}^{t_4^a - T_{a0}^{pick-in}} \left[\left(t_4^a - T_{a0}^{pick-in} - t\right)N_a r_a(t)\right]dt \tag{A.3}$$

Queuing Time

Both early-arriving vehicles and on-time-arriving vehicles need to queue to pick up students. The number of vehicles in the queue is shown in equation (A.4).

$$u_a = \int_{-\infty}^{t_1^a+\Delta t^a} [N_a r_a(t)]dt \tag{A.4}$$

The queuing time $T_2^{pick-wait}$ is shown in equation (A.5).

$$T_a^{car-queue} = \frac{u_a(u_a-1)}{2} \cdot \frac{L_s}{v^{walk}} + u_a \cdot t^{in} \tag{A.5}$$

where v^{walk} is the walking speed, t^{in} is the boarding time, L_s is the length of the berth.

A.2 Passing Vehicles

Due to the presence of on-street parking by escort private cars, passing vehicles within the network experience slowdowns when entering and navigating through the on-street parking zone before accelerating away, resulting in driving delays. Therefore, the delay in travel time T^{pass} for passing vehicles in the parking section is analyzed as its cost.

According to the traffic flow status, the parking section is divided into three segments: a deceleration merging area, a lane reduction area (incorporating on-street parking zones), and a departure area, as depicted in Figure A.1.

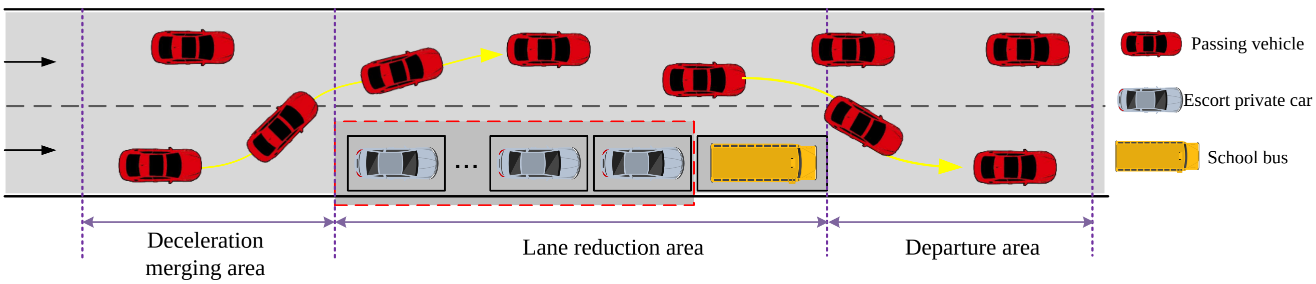

Figure A.1. Parking section

The process for passing vehicles is divided into four stages: vehicle deceleration, lane-changing merging, driving at reduced speed in the reduction area, and accelerated departure. Passing vehicles typically travel at normal speeds. However, due to on-street parking occupying lanes, passing vehicles in affected lanes must slow down and change lanes towards the inner lane, thereby forming a merging area.

Upon entering the lane reduction area following the merging area, all vehicles proceed at speed v_f. Upon exiting the lane reduction area, vehicles accelerate to a steady speed v_e. The travel time delays for passing vehicles in the parking section include vehicle deceleration delay d_d, merging delay d_t, delay due to low-speed driving in the reduction area d_g, and acceleration departure delay d_h.

Deceleration Delay and Acceleration Departure Delay

Assuming all vehicles have the same acceleration during both deceleration and acceleration stages, the deceleration distance $S_d = \frac{v_b^2 - v_f^2}{2a_d}$ for vehicles reducing speed from normal speed v_b to following speed v_f with acceleration a_d, and the deceleration time $t_{decelerate} = \frac{v_b - v_f}{a_d}$ can be calculated. When there is no interference from on-street parking, the time for a vehicle to travel distance S_d is $t_{normal} = \frac{S_d}{v_b} = \frac{v_b^2 - v_f^2}{2a_d v_b}$. Therefore, the delay in deceleration per vehicle is shown in equation (A.6).

$$d_d = t_{decelerate} - t_{normal} = \frac{(v_b - v_f)^2}{2a_d v_b} \quad \text{(A.6)}$$

Similarly, the delay caused by accelerating the vehicle to a steady speed v_e with acceleration a_h is shown in equation (A.7).

$$d_h = \frac{(v_e - v_f)^2}{2a_h v_e} \quad \text{(A.7)}$$

Merging Delay

The traffic wave theory describes the operational state of vehicles in the merging area. When the passing traffic flow speed is v_b, the volume is q_1, and the density is k_1. Upon entering the merging area, a traffic flow queueing wave forms with a wave velocity of v_{s1}. At this point, the traffic flow speed is v_f, the volume is q_2, and the density is k_2.Based on the fundamental equation of traffic wave theory, the wave velocity is determined as equation (A.8).

$$v_{s1} = \frac{q_1 - q_2}{k_1 - k_2} \quad \text{(A.8)}$$

After the traffic flow enters the merging area, the rear end moves backward at speed v_{s1} and the front end moves forward at speed v_f. Therefore, the number of queuing vehicles at time *t* is shown in equation (A.9).

$$NN(t) = (v_f - v_{s1})k_2 t \quad \text{(A.9)}$$

Therefore, the delay incurred during the escort period $[t_1^a, t_3^a]$ is shown in equation (A.10).

$$d_t^a = \int_0^{t_3^a - t_1^a} NN_a(t)\left(1 - \frac{v_f^a}{v_b^a}\right)dt = \int_0^{t_3^a - t_1^a}\left(v_f^a - v_{s1}^a\right)k_2^a t\left(1 - \frac{v_f^a}{v_b^a}\right)dt \quad \text{(A.10)}$$

Since on-street parking occupies the outside lane, vehicles in the outside lane merge using the acceptable gap from the adjacent lane fleet. According to gap theory, the number of vehicles from the outside lane that can merge into the inside lane is determined by equation (A.11).

$$q_{plug} = q_{ave}\frac{e^{-q_{ave}\frac{t_c}{3600}}}{1 - e^{-q_{ave}\frac{t_w}{3600}}} \quad \text{(A.11)}$$

where q_{ave} represents the inside single-lane flow volume $(veh \cdot h^{-1})$, $q_{ave} = \frac{q_1}{s}$; q_{plug} denotes the number of vehicles from the outside lane that can merge into the inner lane $(veh \cdot h^{-1})$; t_c stands for the critical gap that the inside traffic flow can utilize for insertion; t_w indicates the following time of the outside traffic flow. Generally, $t_c = 6 \sim 8s$ and $t_w = 3 \sim 5s$.

Therefore, the traffic flow into the lane reduction area is shown in equation (A.12).

$$q_2 = q_{ave}(s - 1) + min\{q_{ave}, q_{plug}\} \quad \text{(A.12)}$$

Low-Speed Driving Delay

On-street parking occupies road resources, forming a lane reduction area in the road section. The length of this lane reduction area varies over time: it increases gradually as escort private cars arrive successively according to distribution $r(t)$ during $[t_1^a, t_1^a + \Delta t^a]$, remains unchanged during $[t_1^a + \Delta t^a, t_2^a]$, and decreases gradually as escort private cars queue up and leave during $[t_2^a, t_3^a]$.

Suppose a vehicle enters the lane reduction area at time t, and the length of the lane reduction area is $L_a(t)$, which changes to $L_a(t')$ as the vehicle drives out of the lane reduction area at time t'.

Therefore, the delay caused by speed changes before and after encountering on-street parking in the lane reduction area during the escort period $[t_1^a, t_3^a]$ is as follows equation (A.13) - (A.15).

$$d_g^a = \int_{t_1^a}^{t_3^a}\left(\frac{L_a(t')}{v_f^a} - \frac{L_a(t')}{v_b^a}\right)V_2^a(t)dt \quad \text{(A.13)}$$

$$L_a(t') = N_a(t')L_s \quad \text{(A.14)}$$

$$N(t') = \begin{cases} \int_{t_1^a}^{t}[Nr(t')]dt, t' \in [t_1^a, t_1^a + \Delta t^a] \\ u_a, t' \in [t_1^a + \Delta t^a, t_2^a] \\ \frac{u_a}{t_2^a - t_3^a}t' - \frac{t_3^a u_a}{t_2^a - t_3^a}, t' \in [t_2^a, t_3^a] \end{cases} \quad \text{(A.15)}$$

where $V_2(t)$ is the traffic flow of the road section a driving into the lane reduction area $(veh \cdot h^{-1})$, and $V_2^a(t) = q_2^a$. Drive-out time t' satisfies $v_f^a(t' - t) = L_a(t')$.

Hence, the travel delay of all passing vehicles in the section a during the escort period $[t_1^a, t_3^a]$ is as follows equation (A.16).

$$T_a^{pass} = \int_0^{t_3^a - t_1^a}[d_d^a V_1^a(t) + d_h^a V_2^a(t)]dt + d_t^a + d_g^a \quad \text{(A.16)}$$

where $V_1^a(t)$ is the passing traffic flow of section a $(veh \cdot h^{-1})$, $V_1^a(t) = q_1^a$.

A.3 School Buses

After school, the school bus organizes students to disembark based on the parking arrangement of escort private cars. The bus follows a scheduled route from the school to each parking zone, where students disembark and transfer to private cars.

After the transfer, the school bus proceeds to the next parking zone and continues this process until all students have completed their transfer. It's important to note that the same bus can serve multiple parking zones in sequence.

The total school bus time cost T^{bus}comprises both vehicles driving time $T^{bus-drive}$ and dwell time $T^{bus-wait}$.

The driving time of the school bus on the parking road section a is $T_a^{bus-drive}$.

The dwell time m of the school bus in section a is associated with the number of students n_{ma} served by this section. According to the regression model developed by Brace *et al*. (1997), the drop-off service time of school bus m is shown in equation (A.17).

$$T_{ma}^{bus-wait} = 29 + 1.9n_{ma} \qquad \text{(A.17)}$$