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Research Article

A Simulation-Based Optimization Method for Truck-Prohibit Ramp Placement along Freeways

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The increasing number of trucks has a negative impact pertinent to efficiency and safety concerns on the operation of mixed traffic flow along freeways, especially at freeway entrance and exit ramps. To address such issue, this study proposes a simulation-based method for truck-prohibit ramp placement along freeways. The method framework contains two parts: the first part is to generate a set of new truck restriction schemes using simulation experiments, and the second part is to evaluate the generated schemes and find out the current optimal location of truck-prohibit ramps based upon the AHP-TOPSIS method. Three patterns of evaluation indicators are utilized to estimate the performance of freeway service in terms of traffic efficiency, road safety, and accessibility. A case study of the Beijing-Hong Kong-Macao freeway within Henan Province, China, is conducted to verify the effectiveness of the proposed method. Results could provide beneficial insights on the optimal location setting of truck-prohibit ramps to enhance the entire performance of mixed traffic flow along freeways.

1. Introduction

In the wake of ever-growing urbanization and the rapid growth of e-commerce, the number of trucks continuously increases in freeways. Compared with passenger vehicles, trucks have apparent differences in vehicle size, speed, acceleration, and so forth [1]. When trucks and passenger vehicles are mixed in using a freeway service, the state of traffic flow changes significantly, and associated negative impact occurs in terms of efficiency and safety concerns, especially at freeway entrance and exit ramps. As trucks reduce the overall traffic efficiency, mixed traffic may incur traffic congestion, increase the emissions of pollutants, and pose potential safety risks (e.g., [2–8]). To deal with these negative issues, several truck restriction strategies have been proposed to reduce the adverse impact caused by trucks. For example, trucks are prohibited in some freeway segments so as to separate the mixed traffic flow of passenger vehicles and trucks [9]. Nevertheless, it is impossible to restrict trucks on all the road segments at the same time due to transportation needs. Therefore, it is necessary to study specific truck restriction strategies according to the practical circumstances resulted from mixed traffic flow [10]. The implementation of truck restriction strategies in freeways reduces the efficiency of a part of trucks to some extent, but it may be conducive to improving the entire performance of mixed traffic as a whole (e.g., [11–15]).

Regarding freeway truck restriction strategies, the existing studies mainly focus on lane restriction. For instance, El-Tantawy et al. [16] studied the impact of truck restrictions in different lanes based on microscopic traffic simulation and concluded that restricting trucks to the leftmost lane could exert the most influence on traffic efficiency. On this basis, Korkut et al. [17] further analyzed the effect of truck speed restriction in different lanes and obtained the optimal limited speed of trucks in the leftmost lane. Further, Lyons et al. [13] studied the influence of other factors pertinent to truck traffic restriction strategies, including the type of trucks restricted and the time period of truck restrictions. Yet, in the existing literature, little attention is paid to truck restriction strategies at entrance and exit ramps in freeways. As one of the most significant freeway components, the driving state of vehicles at ramps are impressionable to mixed traffic flow, thereby posing bottlenecks and traffic congestions [18]. Thus, it is worth investigating how to design an appropriate truck restriction strategy pertaining to freeway ramps in an effort to improve the entire traffic performance, which is addressed in this study.

Traffic flow is complicated at entrance and exit ramps in freeways because of lane changes and the acceleration or deceleration of vehicles. Further, compared with passenger vehicles, trucks have larger vehicle size and less flexibility, which are easy to adversely affect the operation of mixed traffic flow when vehicles are ready to enter or exit ramps [19]. In view of this problem, we aim to solve it by setting reasonable truck restriction strategies at the ramps. In general, there are several ramps along the freeway within a certain area. Trucks are prohibited entering or exiting one or more ramps, which may be an effective measure to alleviate the above negative impact. Nonetheless, truck ramp restrictions influence the ramp selection of trucks when using the freeway service. Traffic flow varies along freeways, and associated impacts include traffic efficiency, road safety, and accessibility. This study aims to determine which ramps need to implement truck ramp restrictions and to what extent they can influence the performance of freeway service.

To evaluate the performance of freeway service when implementing truck ramp restrictions, several representative evaluation indicators are employed to simultaneously reflect issues about traffic efficiency, road safety, and accessibility. Based on these evaluation indicators, a simulation-based methodology framework is proposed to design the optimal setting of truck ramp restrictions along freeways. The method framework contains two parts, in which the first part is based on the simulation experiment to iterate by using the local search pattern and generate a set of truck restriction schemes, and the second part is to utilize the AHP-TOPSIS approach to evaluate these schemes and single out the optimal scheme.

The simulation-based method has received considerable attention over the last two decades and has been applied in the field of transportation system estimation and optimization. For instance, Siuhi and Mussa [20] compared the influence of high-occupancy vehicle (HOV) lane restriction and truck lane restriction on traffic efficiency based on VISSIM. Al Eisaeia et al. [21] studied the impact of truck restriction on different types of trucks based on VISSIM and determined the optimal truck category to conduct restriction. Fan et al. [22] proposed a surrogate safety assessment model (SSAM for short) and VISSIM for safety assessment at freeway merge areas. Pulugurtha et al. [23] simulated and analyzed traffic accidents based on VISSIM and CORSIM, respectively, and compared the advantages and disadvantages of two simulation softwares. Ge and Yang [24] simulated traffic conflicts based on VISSIM to determine the optimal length of the freeway warning area. Abou-Senna and Radwan [25] utilized VISSIM to investigate the key parameters of CO_2 emissions when vehicles travel on freeways. Those studies have designed different simulation-based methods and reported many interesting findings on the traffic operations in freeways. However, the setting of truck ramp restrictions along freeways by using a simulation-based method has not been particularly studied.

To fill such gap, the main contribution of study is to proposes a simulation-based method framework for determine the optimal prohibited ramp locations for trucks along freeways. The framework contains two parts, in which the first part is based on the simulation experiment to iterate by using the local search pattern and generate a set of truck restriction schemes, and the second part is to utilize the AHP-TOPSIS approach to evaluate and rank these schemes and single out the optimal scheme in each iteration. Once ramps are prohibited for trucks, traffic flow distribution will change as a part of trucks having to alter their routes and use surrounding ramps instead. In such a case, the proposed method considers three evaluation indicators, including traffic efficiency and road safety and accessibility, in an effort to well represent practical circumstances. To the best of our knowledge, this is the first study to propose a generalized method framework for optimizing the truck-prohibit ramp placement along freeways. The proposed method is applied to the case study based on the Beijing-Hong Kong-Macau Expressway within Henan Province, China. Note that though this paper focuses on the truck ramp restriction setting problem, the proposed method has wider applications to other management topics in transportation engineering studies.

The remainder is organized as follows: Section 2 describes the evaluation indicators used in this study. Section 3 describes the methodological framework that is employed to design the placement of restricted ramps for trucks. Section 4 presents the case study. Finally, Section 5 concludes this paper.

2. Evaluation Indicators

A suitable setting of truck-prohibited ramps is an effective measure to alleviate the negative impacts resulting from mixed traffic flow between trucks and passenger vehicles [26]. On one hand, for passenger vehicles, it will undoubtedly provide them with a more flexible and safe driving environment when entering or existing ramps which are prohibited for trucks. Trucks are more aggregated on a limited number of ramps, and the resulting traffic flow distribution may increase the entire performance along freeways [27]. On the other hand, trucks that originally pass through ramps closest to their origins/destinations will have to pass through the adjacent ramps, and the accessibility will be reduced to a certain extent [28]. The abovementioned complex circumstances need to be tackled by simulation techniques like VISSIM.

In recent years, many evaluation indicators have been developed by researchers to evaluate the performance of freeways (e.g., [29–31]. In this study, we select three representative patterns of evaluation indicators to estimate the performance of freeway service when implementing truck ramp restrictions given that truck prohibited ramps are determined.

2.1. Traffic Efficiency. As vehicles with low speeds may delay vehicles with high speeds, road bottlenecks and the resulting vehicle merging are common in multilane traffic systems [32]. Therefore, in terms of traffic efficiency, the average speed $\overline{v}$ and average delay $\overline{d}$ are employed to evaluate the effect of truck-prohibit scheme implementation, which are the direct embodiment of the capacity and service level of the road after truck-prohibit scheme implementation.

2.1.1. Average Speed. The average speed is a parameter that characterizes the smoothness of the road [33]. It is also an intuitive index to evaluate the implementation effect of traffic management measures [34]. The investigation of travel speed involves the measurement of travel time, which can be obtained by taking advantage of software during simulation. In practical engineering, the statistical data of vehicle travel time can be calculated by means of a highway toll gate. The average speed of the vehicles is defined as follows:

$$\overline{v} = \sum_{i=1}^{n} v_i = \sum_{i=1}^{n} \frac{s}{t_i}. \tag{1}$$

As mentioned above, v_i denotes the speed of vehicle i; t_i denotes the travel time of vehicle i; n denotes the number of vehicles at the intersection; and s denotes the travel distance.

2.1.2. Average Delay. The average delay can be used to represent the time lost by vehicles on a road segment due to the traffic flow state. It reflects the difference between the estimated travel time and the actual travel time in the free flow state [35]. It is necessary to measure the delay of different vehicles separately since free-flow travel times vary from vehicle to vehicle [36]. The time loss caused by the traffic flow environment on the road can be directly reflected by calculating the average delay. We define the average delay as follows:

$$\overline{t} = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n_j} \left(t_j - t_{ji} \right)}{\sum_{j=1}^{m} n_j}. \tag{2}$$

As mentioned above, n_j denotes the number of vehicles of type j; t_j denotes the free-flow travel time of the vehicles of type j; and t_{ji} denotes the real travel time of a vehicle i of type j.

2.2. Road Safety. In terms of road safety, the data on traffic accidents are difficult to collect in time, but studies have shown that frequent lane changes on the freeway also have a serious impact on road safety [37, 38]. Since the system can effectively reduce lane changing behavior caused by the movement bottleneck on the lane, the total times of changing lane C can be taken as the safety index of the system in the study.

Times of changing lanes can be obtained directly by simulation software. The formula is as follows:

$$C = \sum_{i=1}^{n} c_i. \tag{3}$$

As mentioned above, c_i denotes the number of times lanes are changed by vehicle i.

2.3. Accessibility. In this paper, we express accessibility by calculating the total distance between the mass center of the traffic area and the ramp. We use ArcGIS software to determine the traffic community and its centroid coordinates along the expressway and then determine the accessibility index by calculating the distance between the centroid of the traffic community and the ramp. The calculation formula for accessibility is as follows:

$$d = \frac{\sum_{i=1}^{n} l_i}{L}. \tag{4}$$

As mentioned above, l_i denotes the average distance from the centroid of traffic community i to the nearby entrance. L denotes the sum of vehicle travel distances from the centroid of all traffic communities to nearby entrances under the initial road network state.

3. Method Framework

Based upon the evaluation indicators in Section 2, we propose a method to determine the optimal prohibited ramp locations for trucks by using VISSIM simulation experiments. The composition of this method framework is shown in Figure 1. It contains two parts, in which the first part is based on the simulation experiment to iterate by using the local search pattern and generate a set of truck restriction schemes, and the second part is to utilize the AHP-TOPSIS approach to evaluate and rank these schemes and single out the optimal scheme in each iteration. These two parts are described in detail below.

3.1. Part I. Regarding Part I, we focus on designing the iterative process based upon VISSIM simulation experiments. In each iteration, we propose ramp selection rules by using the local search pattern to generate a set of truck restriction schemes. On this basis, we conduct a VISSIM simulation experiment for each scheme and obtain the results of associated evaluation indicators.

Specifically, the main body of Part I has two iteration processes. One process is called "added iteration" (A-iteration for short), that is, each iteration aims to add one prohibited ramp for trucks under the conditions of all the ramps in the previous iteration. In such case, only one new truck-prohibit ramp will be added and the conditions of other ramps remain the same. Then, a set of truck restriction schemes is generated. Note that to ensure the accessibility of trucks, any two adjacent ramps cannot be simultaneously prohibited for trucks. When one ramp is set to be truck-prohibited, the associated traffic volume of trucks is assumed

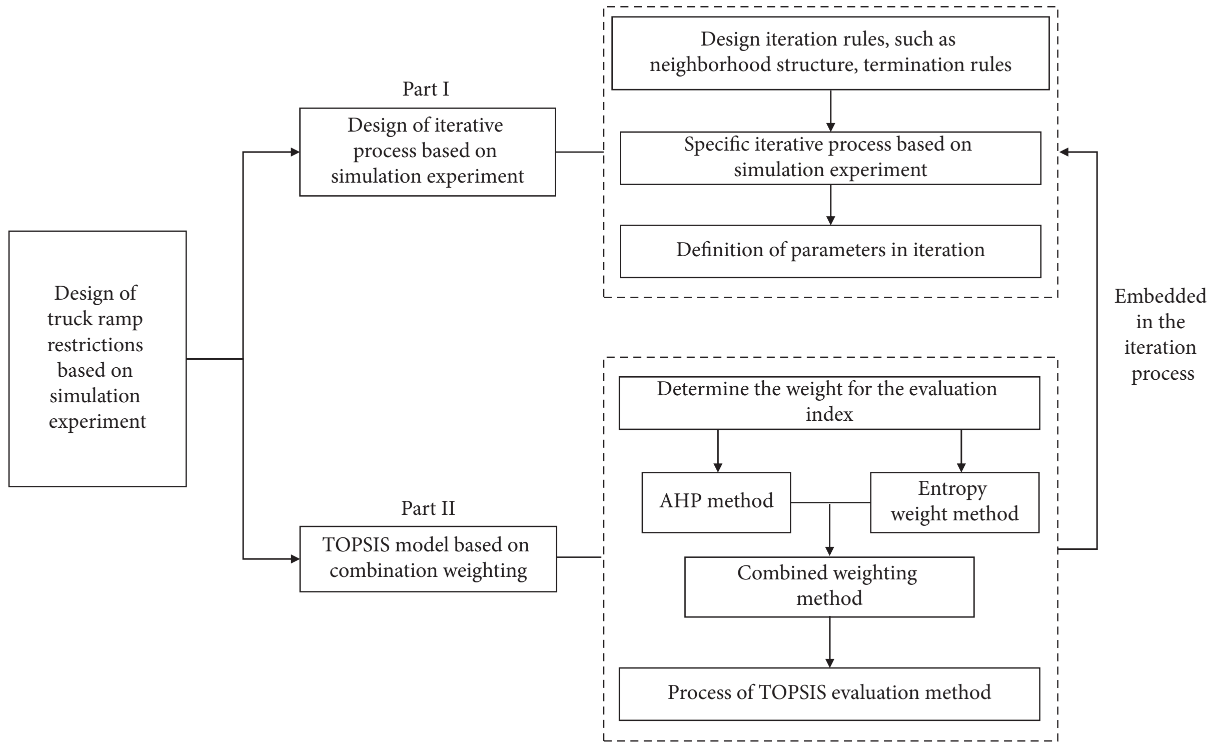

Figure 1: Method framework of this research.

to be evenly distributed to two adjacent ramps. The other process is called "subtracted iteration" (S-iteration for short). It is to delete one prohibited ramp for trucks under the conditions of all the ramps in the previous iteration. A set of new truck restriction schemes is generated in an analogous way as A-iteration.

The method starts with A-iteration, i.e. conducting the local search pattern with neighborhood structure defined as below. The set of new truck restriction schemes is conducted by VISSIM simulation experiments and compared by using the method in Part II. If the best truck restriction scheme in the current iteration is better than the temporarily optimal scheme, it will be treated as the new temporarily optimal scheme, and the information about truck-prohibit ramps will be updated accordingly (in the first iteration, the best scheme will be selected out). Otherwise, the method proceeds with S-iteration. In this way, two processes of Part I are conducted in turn until no better truck restriction scheme can be found.

Neighborhood structure: we let N_a represent the set of ramps that do not set truck restrictions in each A-iteration. Let N_b represent the set of ramps that set truck restrictions in each S-iteration. The neighborhood structure of each iteration is determined by the current solution obtained in the previous iteration (in the first iteration, the current solution is that all the ramps are open to trucks). For A-iteration, we set only one ramp in set N_a to be truck-prohibit each time, and the setting of remaining ramps is unchanged. In such case, a total of $|N_a|$ truck restriction schemes are generated. Similarly, for S-iteration, we reopen only one ramp in set N_b for trucks each time, and the setting of remaining ramps is unchanged. In such case, a total of $|N_b|$ truck restriction schemes are generated. As any two adjacent ramps cannot be simultaneously prohibited for trucks, those schemes that do not satisfy this constraint will be discarded.

The specific steps of two iteration processes are described in detail below.

3.1.1. Process of A-Iteration

Step 1: let the ramp restriction scheme at the current iteration be the temporary optimal scheme, and use X_0 to denote it (At the first iteration, all ramps in X_0 are not restricted).

Set Φ_A to store the neighbor solutions in the current iteration

$N_a = \text{list}[\text{unrestricted ramps in } X_0]$

Set $n = 0$;

while $n \leq |N_a|$

  let ramp $N_a[n]$ be truck-prohibit and generate a neighbor solution X_n

  if X_n satisfy the adjacent ramp constraint,

    record the ramp restriction scheme X_n in Φ_A

  end if

  let ramp $N_a[n]$ be unrestricted ramps

  $n = n + 1$

end while

Step 2: conduct VISSIM simulation experiment for each scheme in Φ_A, and record the output results of indicators.

Step 3: determine the best truck restriction scheme. Use AHP-TOPSIS method in Part II to evaluate the schemes in set Φ_A and X_0, and select the scheme with the highest score as the best truck restriction scheme.

Step 4: judge whether the best truck restriction scheme in the set Φ_A is better than X_0. If yes, replace X_0 with the best truck restriction scheme, return to step 1, and update N_a. If not, and the stopping criterion is not satisfied, stop the current A-iteration and output X_0.

3.1.2. Process of S-Iteration

Step 1: let the ramp restriction scheme at the current iteration be the temporary optimal scheme, and use X_0 to denote it.

Set Φ_S to store the neighbor solutions in the current iteration

$N_s = \text{list}[\text{truck} - \text{prohibited ramps in } X_0]$

Set $n = 0$;

while $n \leq |N_s|$

let ramp $N_s[n]$ be truck-unrestricted and generate a neighbor solution X_n

if X_n satisfy the adjacent ramp constraint,

record the ramp restriction scheme X_n in Φ_S

end if

set ramp $N_a[n]$ be truck-prohibited ramps

$n = n + 1$

end while

Step 2: conduct VISSIM simulation experiment for each scheme in Φ_S, and record the output results of indicators.

Step 3: determine the best truck restriction scheme. Use AHP-TOPSIS method in Part II to evaluate the schemes in set Φ_S and X_0, and select the scheme with the highest score as the best truck restriction scheme.

Step 4: judge whether the best truck restriction scheme in the set Φ_S is better than X_0. If yes, replace X_0 with the best truck restriction scheme, return to step 1, and update N_a. If not, and the stopping criterion is not satisfied, stop the current S-iteration and output X_0.

3.1.3. Iteration Flow Framework. A flowchart is provided to demonstrate the whole iterative process, as shown in Figure 2.

3.2. Part II. In Part II, we focus on the design of the AHP-TOPSIS evaluation approach to estimate a set of ramp restriction schemes. In the evaluation process, we combine the AHP and the entropy method to determine the weight of each of the four indicators in Section 2. On this basis, we use the TOPSIS model to evaluate the truck restriction schemes generated in Part I.

When evaluating the truck restriction schemes generated in Part I, the reliability of the evaluation results depends on whether the setting of indicator weights is reasonable. In order to avoid the shortcomings of subjective setting, we improve the traditional TOPSIS approach. Specifically, we first use the AHP and entropy methods to determine the weight of each indicator, respectively. Then, we use the multiplication combination weighting method to determine the final weight. After the weights are determined, we use the AHP-TOPSIS method to evaluate a set of truck restriction schemes and rank them based on their evaluation results, thereby finding the optimal scheme.

3.2.1. Determine Weight

(1) AHP Method. AHP (analytic hierarchy process) is an effective method to solve fuzzy problems [39]. It establishes a priority scale based on the subjective judgment of domain experts and makes evaluations of variables according to priority (e.g. [40, 41]. The steps of the AHP method are as follows:

Step 1: build a judgment matrix A at all levels

Based on the hierarchical structure model, the indexes of the same level are compared with each other to determine the relative importance of the indexes of the same level. The value of each element a_{ij} ($i, j = 1, 2, \ldots, h$) in the judgment matrix A represents the importance of factor i relative to factor j.

Step 2: solve the eigenvector of the judgment matrix A

We use the square root method to calculate the approximate value of the eigenvector of matrix A to obtain the vector M, the formula is shown as follows:

$$M_i = \sqrt[h]{\prod_{j=1}^{h} a_{ij}}. \tag{5}$$

Then, we normalize M to obtain the eigenvector W; the formula is shown as follows:

$$W_i = \frac{M_i}{\sum_{i=1}^{h} M_i}. \tag{6}$$

At last, we calculate the maximum characteristic root of the judgment matrix A; the formula is as follows:

$$\lambda_{\max} = \sum_{i=1}^{h} \frac{(AW)_i}{hW_i}. \tag{7}$$

$(AW)_i$ represents the i-th element of vector AW.

Step 3: consistency test

It is necessary to calculate whether the judgment matrix can pass the consistency test. The formulas are as follows:

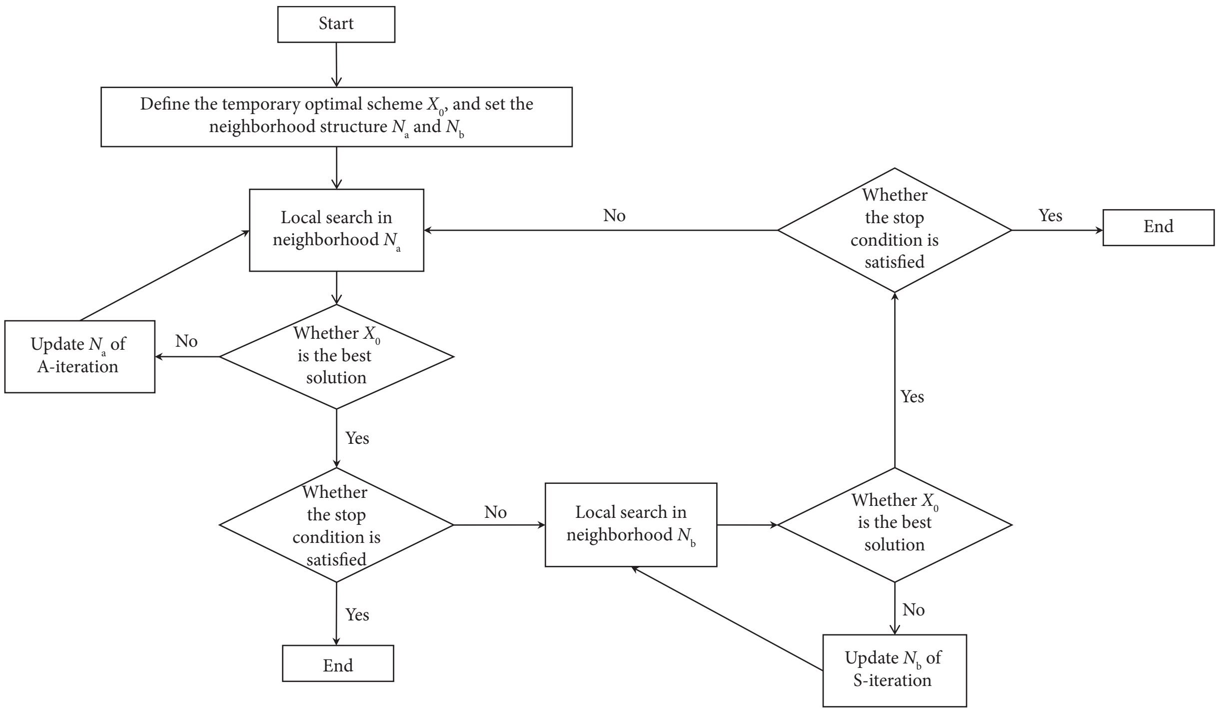

Figure 2: Flowchart of the iteration.

$$\mathrm{CI} = \frac{\lambda - h}{h - 1}, \quad (8)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \quad (9)$$

In the abovementioned, CI denotes the consistency index to measure the deviation of the judgment matrix A. CR denotes the consistency ratio. When CR < 0.1, the judgment matrix A passes the consistency test, otherwise the matrix should be reconstructed until it passes the test.

Step 4: obtain AHP weight

After the abovementioned steps, the weight vector passing the consistency test can be obtained. It is the weight of the index in this layer, and we use $\alpha_j\,(j = 1, 2, \ldots, h)$ to represent it. It shall meet the following conditions: $\sum_{j=1}^{h} \alpha_j = 1, \alpha_j \geq 0$.

(2) Entropy Weight Method. The entropy method based on information theory is an objective weighting method to determine the index weight according to the difference in the information order degree of each index, which only depends on the dispersion degree of the data itself [42]. The calculation steps are as follows:

Step 1: establish initial evaluation matrix

There are m alternatives and h evaluation attributes to form the initial evaluation matrix $Q = (x_{ij})_{m\times h}$, and x_{ij} represent the observed value of the i-th scheme on the j-th index.

Step 2: data normalization processing

To eliminate the influence of different data dimensions on the evaluation results, each index needs to be normalized. Average speed and accessibility indicators are positive indicators. That is to say, the larger their value is, the better the result is. The method to normalize the positive indicators is shown as follows:

$$x'_{ij} = \frac{x_j - x_{\min}}{x_{\max} - x_{\min}}. \quad (10)$$

For average vehicle delay and times of changing lanes which are negative indicators, the smaller their value is, the better the result is. The method to normalize the negative indicators is shown as follows:

$$x'_{ij} = \frac{x_{\max} - x_j}{x_{\max} - x_{\min}}. \quad (11)$$

In the abovementioned, x_j denote the value of the j-th index; $x_{\max}$ denote the maximum value of the j-th index; and $x_{\min}$ denote the minimum value of the j-th index.

Step 3: calculate the entropy value of each index

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}, \quad (j = 1, 2, \ldots, h). \quad (12)$$

In the abovementioned, k is related to the number of schemes and is often taken as $1/\ln m$; p_{ij} denote the proportion of the j-th index in the i-th truck traffic restriction scheme and is often taken as $x'_{ij}/\sum_i^m x'_{ij}$. m denotes the number of schemes. In addition, if $p_{ij} = 0$, then make $p_{ij} \ln p_{ij} = 0$.

Step 4: obtain the entropy weight

$$\beta_j = \frac{1-e_j}{\sum_{j=1}^{h}(1-e_k)}, \quad (j = 1, 2, \ldots, h). \tag{13}$$

In the abovementioned, β_j denotes the weight coefficient of the j-th evaluation index.

(3) Determination of Combination Weight. To make the final index weight combine subjective preference with objective information from the data, we need to properly deal with the weight obtained by the objective evaluation method and the subjective evaluation method to get the final weight. Since it is not suitable to increase the subjective preference of weight when the AHP method has been used, we weigh with multiplicative combinations to determine the final combination weight in this study, and the calculation formula is shown as follows:

$$w_j = \frac{\alpha_j \beta_j}{\sum_{j=1}^{h} \alpha_j \beta_j}. \tag{14}$$

In the abovementioned, w_j represents the weight of the combination.

3.2.2. AHP-TOPSIS Model. The TOPSIS method is a commonly used intragroup comprehensive evaluation method, which can make full use of the information in the original data. Its results can accurately reflect the gap between evaluation schemes [43]. This method has no strict restrictions on data distribution, and data calculation is simple and easy [44]. Combined with the weights obtained in Section 3.2.1, this section will introduce the calculation steps of the AHP-TOPSIS model.

Step 1: homogeneity of index attributes and normalization

In this paper, we adopt the range standardization method to make standardization for the index values of four indicators to transform cost-effective indicators into benefit-oriented indicators. The calculation formulae are the same as (10) and (11).

Step 2: construct the original data matrix

Assuming that m denotes the number of schemes and h denotes the number of evaluation indexes, the original data matrix after the homogeneity of index attributes is shown as follows:

$$X = \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{1h} \\ X_{21} & X_{22} & \ldots & X_{2h} \\ \ldots & \ldots & \ldots & \ldots \\ X_{m1} & X_{m2} & \ldots & X_{mh} \end{bmatrix}. \tag{15}$$

Step 3: determine the weight of the evaluation index

This paper combines the AHP method and the entropy weight method to obtain the weight of each index. We determine the combined weight vector as $w = (w_1, w_2, \ldots w_h)$. w_j denote the weight coefficient of the j-th index.

Step 4: construct a normalization matrix

We normalize the vector of the indicator attribute, that is, each column element is divided by the vector norm of the current column. The formula is shown as follows:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}. \tag{16}$$

x_{ij} represents the observed value of the i-th (i = 1, 2, 3, . . ., m) scheme on the j-th (i = 1, 2, 3, . . ., h) index.

We get the standardized matrix by this process and show it as follows:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & \ldots & Z_{1h} \\ Z_{21} & Z_{22} & \ldots & Z_{2h} \\ \ldots & \ldots & \ldots & \ldots \\ Z_{m1} & Z_{m2} & \ldots & Z_{mh} \end{bmatrix}. \tag{17}$$

Step 5: determine positive and negative ideal solutions

The positive ideal solution Z^+ consists of the maximum value of each column element in Z, that is,

$$Z^+ = (\max(z_{11}, z_{21}, \ldots, z_{m1}), \max(z_{12}, z_{22}, \ldots, z_{m2}), \ldots, \max(z_{1h}, z_{2h}, \ldots, z_{mh})) = (Z_1{}^+, Z_2{}^+, \ldots, Z_h{}^+). \tag{18}$$

The negative ideal solution Z^- consists of the minimum value of each column element in Z, that is,

$$Z^- = (\min(z_{11}, z_{21}, \ldots, z_{m1}), \min(z_{12}, z_{22}, \ldots, z_{m2}), \ldots, \min(z_{1h}, z_{2h}, \ldots, z_{mh})) = (Z_1{}^-, Z_2{}^-, \ldots, Z_h{}^-). \tag{19}$$

Step 6: calculate the closeness between the positive and negative ideal solution in each scheme:

$$R_i = \frac{D_i^-}{D_i^+ + D_i^-}. \tag{20}$$

In the abovementioned, D_i^+ denotes the proximity between the i-th freight train restriction scheme and the optimal scheme, and the calculation formula is shown as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{h} w_j \left(Z_j^+ - z_{ij}\right)^2}. \tag{21}$$

D_i^- denotes the proximity between the i-th restriction scheme and the worst scheme, and the calculation formula is shown as follows:

$$D_i^- = \sqrt{\sum_{j=1}^{h} w_j \left(Z_j^- - z_{ij}\right)^2}. \tag{22}$$

In the abovementioned, w_j denotes the weight coefficient of the j-th index, and $0 \le R_i \le 1$. The closer the R_i is to 1, the better the scheme.

4. Case Study

For any freeway segment, the geometric characteristics of roads needs to be first imported into VISSIM software to build the simulation scenario of the case study. Later, traffic flow data is also imported to obtain the values of three evaluation indicators, including traffic efficiency, road safety, and accessibility, by using VISSIM. On this basis, we can utilize the proposed simulation-based method framework to obtain the optimal locations of truck-prohibit ramps along the freeway segment. In this section, we select a part of the Beijing-Hong Kong-Macao Freeway within Henan Province, China, as the case study. This freeway segment is located near the city of Zhengzhou in Henan Province, China, containing twelve freeway ramps. The traffic flow is large, and traffic congestions often take place at these freeway ramps. We use ArcGIS software to draw the surrounding sections and divide the area near the road into 13 traffic areas according to the traffic sources and administrative division of the ramps nearby. The distribution map of 13 traffic areas and 12 ramps is shown in Figure 3.

Along the freeways, it is a four-lane freeway section with a lane width of 3.75 m. Two slow lanes and two fast lanes are set in this section, respectively. Trucks are required to drive only in the slow lane, while cars are allowed to drive in any lane. The speed limit is 100–120 km/h on the fast lanes and 80–100 km/h on the slow lanes. In this paper, we collect data on traffic flow at peak hours and transit traffic volume at the ramps. In peak hours, the total traffic flow of the 12 ramps is about 1588 vehicles per hour. Among these vehicles, about 1190 are passenger vehicles, accounting for 75% of the total, and the rest are 398 trucks. The volume of traffic during peak hours is about 340 vehicles per hour, as shown in Table 1.

This paper uses simulation software to establish a simulation model for this section. The settings and parameters of driving behavior, lane change behavior, and signal control are the same as those based on the Wiedemann99 model.

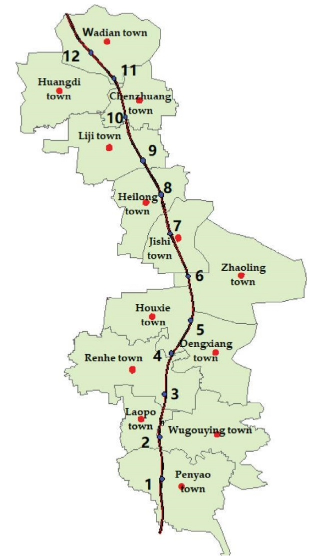

Figure 3: Locations of ramps and traffic communities of the Beijing-Hong Kong-Macao freeway.

Table 1: Traffic input at peak hours.

Category	Volume (PCU/h)	Proportion (%)
Passenger vehicles	482	75
Trucks	1448	25
Total	1930	100
Traffic at ramps	1588	82.3
Transit traffic	342	17.7
Total	1930	100

There are four evaluation indexes selected in this case, namely, average speed, vehicle delay, accessibility, and times of changing lanes. When using the analytic hierarchy process to assign weights, the weighting results based on the nine-level scale are shown in Table 2.

Consistency test: the calculated random index RI was used to measure consistency by consistency ratio [45]. From the abovementioned table, $\lambda_{\max} = 4.0104$. According to the RI table, the corresponding RI value is 0.882, $CR = CI/RI = 0.0039 < 0.1$. It passes the consistency test.

After using the AHP method to determine the weight of the four indexes, we carry out simulation experiments according to the iteration rules. In each iteration, we use the entropy method to determine the objective weight and combine the objective weight with the weight achieved by the AHP method to get the final weight. We use the TOPSIS evaluation method to grade the schemes based on the final weight and rank the schemes by composite scores. After five iterations, we achieve the final scheme. The values of the combined weights in the final iteration are shown in Table 3. The final results show that the best effect is to restrict truck traffic at ramps 4, 6, and 11. The specific index data of the optimal scheme are shown in Table 4.

In general, compared with the initial section without any restrictions, the proposed scheme sets restrictions on trucks at three ramps. This scheme reduces traffic conflicts and

Table 2: Weighting results of the AHP method.

Items	Eigenvectors	Weighting values	Largest eigenvalues	CI ratios
Average speed	1	0.2274	4.0104	0.0035
Average delay	1	0.2274		
Accessibility	0.5373	0.1222		
Times of changing lane	1.8612	0.4231		

Table 3: Value of the combined weight.

Items	Weight value of AHP (α_j)	Weight value of entropy weight method (β_j)	$\alpha_j\beta_j$	w_j
Average speed	0.2274	0.256	0.058214	0.237
Average delay	0.2274	0.255	0.058669	0.239
Accessibility	0.1222	0.258	0.031161	0.127
Times of changing lane	0.4231	0.231	0.097736	0.398

Table 4: Index data of the final scheme and the initial scheme.

Ramps which restrict cargo vehicles	Average speed (km/h)	Average delay (s)	Accessibility	Times of changing lane (times)
4, 6, 11	97.577	1.881	0.89	4127
None	97.152	2.410	1	4355

Table 5: Comparison of passenger vehicle index data before and after implementation.

Passenger vehicles	Average speed (km/h)	Percentage of change (%)	Average delay (s)	Percentage of change (%)
Before implementation	104.091	0.343	2.663	25.65
After implementation	104.448		1.980	

Table 6: Comparison of truck index data before and after implementation.

Cargo vehicles	Average speed (km/h)	Percentage of change (%)	Average delay (s)	Percentage of change (%)
Before implementation	77.198	0.525	1.685	5.58
After implementation	77.603		1.591	

vehicle delays at the ramps of the freeway and improves the efficiency and safety of the freeway. Compared with the existing road section, although some sections with the restriction strategy show the increased travel mileage of some trucks at the entrance and exit, the average speed of each vehicle on the road section increases by 0.44%, the delay per vehicle decreases by 21.95%, and the number of lane changes decreases by 5.24%. Therefore, the traffic efficiency of this section has been significantly improved, and the traffic safety has been improved as well.

In addition, in order to discuss the impact of truck restrictions at ramps on trucks and passenger vehicles, we compared the traffic efficiency indexes of trucks and passenger vehicles before and after optimal truck-prohibition scheme implementation. Tables 5 and 6 show the data comparison results of trucks and passenger vehicles, respectively.

It can be seen that the truck ramp restrictions could not play a significant role in improving the speed of trucks and passenger vehicles, but they can effectively reduce vehicle delay. Through the implementation of this strategy, the delay time of trucks is reduced by about 5.58%, and the delay time of passenger vehicles is reduced by about 25.65%. This indicates that the proposed strategy has a significant effect on improving the efficiency of passenger cars.

In addition, although setting truck restrictions at specific ramps will increase the driving distance of some trucks at specific ramps and increase the traffic volume of trucks at adjacent ramps, the strategy proposed by us does not lead to further congestion of trucks on freeways on the whole but reduces the delay time of trucks. Therefore, the passenger vehicle separation strategy at freeway ramps proposed in this paper can improve the efficiency of roads, passenger vehicles, and trucks at the same time. The comparison results also verify the effectiveness of the optimal truck-prohibited scheme.

5. Conclusion

Trucks negatively impact the operation of mixed traffic flow along freeways, especially at freeway entrance and exit ramps. By setting up the appropriate truck ramp restrictions, the associated negative influence can be alleviated, thereby improving the performance of the entire freeway service. To this end, this study proposes a generalized simulation-based method framework for determine the optimal prohibited ramp locations for trucks along freeways. The originality of the method framework is worth noting: (1) we use three representative patterns of evaluation indicators to signify the performance of freeway service in terms of traffic efficiency, road safety, and accessibility. (2) the method framework contains two parts, in which the first part is based on the simulation experiment to iterate by using the local search pattern and generate a set of truck restriction schemes, and the second part is to utilize the AHP-TOPSIS model to evaluate and rank these schemes and single out the optimal scheme in each iteration. The method takes the effects of all the candidate truck ramp restrictions into account, and two different iterative mechanisms are tailored to avoid the solution falling into the local optimal trap. A case study of the Beijing-Hong Kong-Macao expressway within Henan Province of China is conducted to verify the effectiveness of the proposed method. Results could provide beneficial insights on the optimal location setting of truck-prohibit ramps to enhance the entire performance of mixed traffic flow along freeways.

Admittedly, this study comes with some limitations, and the following improvements are suggested: (1) environment issues can be further considered in truck-prohibit ramp placement. Vehicle emission models need to be particularly investigated while considering different scenarios of diesel, electric, and hybrid trucks and passenger vehicles. (2) the method could be extended to obtain dynamic truck ramp restriction schemes at the operational level when high-resolution traffic flow data is available. The authors recommend that future studies focus on these issues.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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