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Optimization of Ramp Locations along Freeways: A Dynamic Programming Approach

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Abstract: Ramps provide entrances and exits for residents to conveniently use the freeway service. Due to the high construction cost and geometric design requirements, the decision of ramp locations involves a trade-off between multiple influencing factors, such as accessibility, safety, efficiency, construction costs, etc. This study proposed a methodology for optimizing freeway ramp placement in an effort to improve freeway accessibility. The freeway ramp locating problem was formulated as a bi-objective optimization model. Two objectives were pertinent to the reduction of total social costs: the minimization of total travel cost and minimization of total construction cost. To reflect the safety concern of ramp locations, the frequency of lane changes around the ramps and the minimum spacing between ramps were constrained. We developed an exact solution method based upon dynamic programming to solve the proposed model. Finally, a case study of the Beijing–Hong Kong–Macau Expressway within Henan Province, China, was conducted to verify the effectiveness of the proposed model and solution method.

Keywords: freeway accessibility; ramp placement; optimization; dynamic programming approach

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1. Introduction

As one of the most important channels between cities, the freeway service plays a pivotal role in urban economic development [1]. In general, freeways are used to efficiently connect different cities [2]. With the expansion of cities and rapid progress of urbanization, traffic demand in both urban and surrounding rural areas has been continuously increasing in the past decades. More than ever, the service level and accessibility of freeways require efforts to be enhanced to promote convenient access services for both urban and surrounding rural residents and to achieve sustainable development of road traffic. Ramps are the connecting infrastructures between freeways and urban roads, providing entrances and exits for residents to use the associated freeway service [3]. Yet for rural traffic needs, the existing ramps are currently located far away and inconvenient to use. It seems to be necessary to locate more freeway ramps, which are conducive to improving accessibility for rural residents. Meanwhile, the freeway ramp placement problem is an important issue involving the efficiency, safety, and accessibility of the freeway service [4–7]. Optimized ramp placement allows for improving freeway services and even reducing environmental impact [8]. Therefore, the idea of whether freeway accessibility determines ramp locations deserves to be particularly investigated, which we tackled in this study.

Previous studies focused on single ramp spacing and provided recommended values for various scenarios. Considering safety and mobility around the ramp, driving behavior is regarded as the key controlling factor when developing normative spacing between ramps [9]. Vehicles passing through freeway ramps and weaving areas can induce lane changes and acceleration/deceleration of traffic [10]. Further, many guidelines provided criteria for the spacing of ramps by analyzing vehicle operating characteristics in the weaving section [11–13]. For instance, HCM (2010) [11] proposed a set of recommended ramp spacings based on the needs of basic freeway segments where cars merge, diverge, and weave. Pei [14] determined minimum ramp spacing by calculating the minimum acceleration and deceleration lengths based on the driver's decision. In addition, mandatory lane changes increase around freeway ramps and weaving areas, which were shown to negatively affect traffic safety and operations [10]. Several studies [15–19] constructed regression models to explore the relationship between ramp spacing and safety based on relevant crash data (i.e., freeway geometric characteristics, traffic characteristics, crash counts, etc.). Thanh Q [17] asserted that the expected number of crashes increases with a decrease in ramp spacing. Consequently, the spacing of ramps should have a lower bound threshold to ensure vehicle mobility and safety around the ramps. Furthermore, researchers applied simulation software to demonstrate the factors and characteristics of ramp traffic. For example, Chen [20] used a VISSIM simulation to determine effective ramp spacing in different scenarios. In conclusion, the research on single ramp spacing has provided substantial results to guide the design of freeway ramp spacing in different scenarios.

In practice, there are multiple on-ramps and off-ramps located along the freeway within a specific district (e.g., one province). The research on single ramp spacing can only reveal microscopic vehicle safety and efficiency around the ramp. However, it is difficult to depict the effects of multiple ramps at the network level, such as service accessibility at diverse demand points (e.g., towns) along the freeway. One of the most essential concerns for ramp location is the accessibility of freeways, which reflects convenience for citizens [21]. Generally, travelers prefer to access the freeway at the nearest on-ramp from their origins and exit the freeway at the nearest off-ramp. The density and locations of freeway ramps are usually used to determine the access time of freeway service. However, traffic demand along the freeway cannot be satisfied by constructing too many ramps as the construction cost of ramps also needs to be considered. Due to the high cost of infrastructure projects such as highways, the accuracy of the project cost estimate is critical to the success of the project [22,23]. In summary, when designing a freeway network, the minimum number of ramps should be limited to ensure that travelers can access freeway service within a minimum reasonable distance. Meanwhile, the construction of the freeway project may incur economic and technical challenges due to an excessive number of ramps along the freeway. Consequently, determining the locations of highway ramps is not trivial as it necessitates simultaneously striking a tradeoff among accessibility, construction cost, and other concerns. This study took these elements into account at the same time and presented an approach for solving the freeway ramp location problem.

Given influence factors such as accessibility and construction costs, etc., the design of ramp placement requires overall consideration. Previous methods of determining ramp locations along the freeway can be divided into two streams. (i) The first method is to evaluate different ramp location schemes using comprehensive indicators to obtain the optimal one. This method has been extensively studied and usually includes the analytic hierarchy process [24], fuzzy comprehensive evaluation method [25], and matter element method [26]. For example, Liu [25] applied the fuzzy comprehensive evaluation method to quantitatively evaluate the connectivity of the freeway ramps with the urban road network. (ii) The second method is to consider the ramp placement as a discrete optimization problem and select the optimal solution from the candidate ramps. Deng [27] proposed a bi-level optimization model to solve the problem of locating the freeway ramps. The upper level minimized the construction cost, transportation network improvement cost, and travel cost, while the lower level was a standard user equilibrium assignment problem that used mode accounting for the drivers' path choice behavior. Nevertheless, discrete optimization models for locating the ramps along a freeway are in scant supply, which we addressed in this study.

The objective of this study was to propose a methodology for the optimization of ramp locations along freeways. Considering practical circumstances, citizens can benefit from the addition of ramps to freeways as they shorten the access distance for residents within the freeway's service district. Meanwhile, ramp spacing needs a lower boundary limit to ensure freeway safety and operational efficiency. Two objectives were considered in this study: the minimization of total travel cost and minimization of total construction cost. Both objectives aimed to reduce the total social costs and some constraints to reflect practical circumstances (e.g., road safety). The proposed model was solved using an exact solution method based upon dynamic programming.

The remainder of this paper is organized as follows. Section 2 describes the problem and establishes the optimization model, and the solution method is depicted in Section 3. A case study is presented in Section 4. Finally, conclusions are given in the last section.

2. Problem Statement and Model Development

In this study, we considered ways to optimize ramp locations along one freeway within a specific district (e.g., one province). The freeway in a district attracts traffic demand from a set of cities, counties, and towns (for ease of representation, these were each dubbed as traffic regions), which are sequentially numbered as $i = 1, 2, \ldots, M$. Along the freeway, existing ramps and candidate ramps are sequentially numbered as $j = 1, 2, \ldots, N$. Each ramp location contains at least one on-ramp and one off-ramp that are used to serve the surrounding traffic regions. Each ramp location has its particular service area, and we assume that only vehicles located in such service area will consider using the freeway by entering the on-ramp or exiting the off-ramp. Note that the service area may contain one or more traffic regions. Variables/parameters used in the model and their notation are summarized in Table 1.

Table 1. List of Notations.

Variable	Notation
Indices	
i	Index of traffic regions
j	Index of existing ramps and candidate ramps
g	Index of traffic regions along the freeway section between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
Parameters	
C_a	Cost of access time
C_f	Cost of freeway travel time
C_s	Construction cost
d_{gj}	Distance between traffic region g and ramp j
p_{gj}	Distance decay probability between traffic region g and ramp j
Q_g	Travel demand of travel region g
q_{gj}	Traffic demand between traffic region g and ramp j
φ_a	Unit value of access cost
$\overline{v}_a$	Average access speed
V_{jk}	Traffic volume between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
t_f^{jk}	Travel time between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
$\overline{v}_f$	Average free-flow travel speed on the freeway
c	Freeway capacity
t_d^{jk}	Travel delay existing in the location between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
e	Critical gap acceptance for vehicles entering or exiting the ramps
m_{jk}	Average waiting interval between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
T_{jk}	Average non-gap duration between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$
λ_j	Average vehicle arrival rate of ramp j
φ_f	Unit value of freeway travel cost
C_j	Construction cost of ramp j

Table 1. *Cont.*

Variable	Notation
γ_s	Service life of freeway
H_{jk}	Number of lane-changing behaviors between ramp j and ramp k
H_{max}	Maximum number of lane changes
L_{jk}	Spacing between ramp j and ramp k (j = 1, 2, ... , $N - 1$)
L_{min}	Lower limit of the spacing
Sets	
G_g	Set of available ramp locations of traffic region g
S	Set of existing ramps
$\overline{S}$	Set of existing ramps and selected candidate ramps
Variables	
x_j	Binary variable that equals 1 if ramp j ($j \notin \overline{S}$) is selected to be newly constructed ramps and 0 if otherwise
j	Index of existing ramps and candidate ramps
k	Downstream ramp of ramp j

Once candidate ramps are decided to be constructed along the freeway, the distribution of traffic demand may change. The ramps will provide convenience for more travelers since vehicles in some traffic regions will have easier access to freeway service using newly constructed ramps. On the other side, a negative impact of constructing more ramps is that the government needs spend additional cost. Furthermore, travel time may change due to the variation of traffic demand resulting from newly constructed ramps. Simultaneously, newly constructed ramps may lead to fluctuations in the frequency of lane-changing behavior as vehicles enter and exit the freeway, which potentially poses safety concerns. Thus, a methodology is needed to investigate the trade-off between the two objectives and to optimally plan ramp locations with the lowest total social cost.

The total social cost in the optimization model considered two objective terms: minimizing the cost of travel time (including access time and freeway travel time) and minimizing the construction cost. For the ease of model formulation, we let k denote the downstream ramp of ramp j. The traffic regions along the freeway section between ramp j and ramp k were then sequentially numbered as g = 1, 2, ... , M_{jk}. Meanwhile, we defined set S = the set of existing ramps and $\overline{S}$ = the set of existing ramps and selected candidate ramps. x_j was defined as the decision variable that equals 1 if ramp j ($j \notin S$) was selected to be newly constructed ramps and 0 if otherwise.

2.1. Total Travel Cost

2.1.1. Access Cost

Accessibility is an important issue that determines whether travelers are willing to use the freeway service [21]. In this study, each traffic region was represented by a node known as a centroid. Accessibility can be measured by the access time between the centroid and ramp locations [28]. For any traffic region g between ramp j and ramp k, we assumed that only ramp locations (including existing or newly constructed) for which the associated access time was not more than τ would be used by travelers. G_g denoted the set of available ramp locations of traffic region g. The demand of traffic region g was distributed among the ramps in set G_g, and the distance decay function was applied to calculate the probability of traffic demand distribution [29]. The distance decay probability was calculated as below:

$$\mathrm{p}_{gj} = \frac{{d_{gj}}^{\delta}}{\sum_{j \in G_g} {d_{gj}}^{\delta}} \tag{1}$$

where d_{gj} was defined as the distance between traffic region g and ramp j and the parameter δ was the distance decay coefficient, for which the value derived by Cui [30] is -0.1022. Q_g

denoted the travel demand of travel region g. The traffic demand between traffic region g and ramp j, denoted by q_{gj}, was then calculated as:

$$q_{gj} = Q_g \cdot p_{gj} \tag{2}$$

The access cost between ramp j and ramp k (C_a) was the sum of the access cost of all traffic regions (1, 2, ... , M_{jk}). For demand q_{gj}, access time equaled the product of traffic demand q_{gj} and associated access time $d_{gj}/\overline{v}_a$ per trip, for which $\overline{v}_a$ was the average access speed of vehicles. The total access time C_a equaled:

$$C_a(j,k) = \varphi_a \cdot \sum_{g=1}^{M_{jk}} \frac{q_{gj} d_{gj}}{\overline{v}_a} \tag{3}$$

where φ_a denoted the value of vehicle access time.

2.1.2. Freeway Travel Cost

Efficiency impacts the service level of travelers using the freeway [31]. In this study, efficiency was expressed as freeway travel cost, which is the sum of freeway travel time cost of all traffic demand. For each vehicle, freeway travel time involves two factors: the first factor is the travel time along the freeway, and the second factor is the travel delay existing at the ramp location (either exiting off-ramp or entering on-ramp).

According to the Bureau of Public Road (BPR) function, the travel time along the freeway depends on the traffic volume of vehicles, free-flow travel time, and road capacity [10]. We defined V_{jk} as the traffic volume between ramp j and ramp k along the freeway, and L_{jk} denoted the spacing between ramp j and ramp k. The travel time along the freeway of vehicles between ramp j and ramp k, t_f^{jk}, was then determined as:

$$t_f^{jk} = \frac{L_{jk}}{\overline{v}_f}\left[1 + \alpha\left(\frac{V_{jk}}{c}\right)^{\beta}\right] j = 1, 2, \ldots, N-1 \tag{4}$$

where $\overline{v}_f$ illustrated the average free-flow travel speed on the freeway, c denoted freeway capacity, and α and β represented impedance parameters whose recommended values are 0.15 and 4, respectively.

The travel delay existing at the ramp location was caused by waiting for an acceptable gap when entering or exiting the ramps. We then assumed that the arrival time of vehicles obeyed Poisson distribution. According to the gap acceptance theory [32,33], the average waiting interval between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$, w, equals:

$$w_{jk} = \frac{1}{e^{-V_{jk}\varepsilon}} - 1 \tag{5}$$

where ε illustrates the critical gap acceptance for vehicles entering or exiting the ramps.

The average non-gap duration of between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$ was determined by:

$$T_{jk} = \frac{1}{V_{jk}} - \frac{\varepsilon e^{-V_{jk}\varepsilon}}{1 - e^{-V_{jk}\varepsilon}} \tag{6}$$

The average travel delay per vehicle at between ramp j and ramp k $(j = 1, 2, \ldots, N-1)$, t_d^j, was then expressed as Equation (7):

$$t_d^{jk} = \left(\frac{1}{w_{jk} T_{jk}} - \lambda_j\right)^{-1} \tag{7}$$

where λ_j represented the average vehicle arrival rate of ramp j.

The freeway travel cost was taken to be the sum of the total travel time along the freeway (t_f^{jk}) plus the total travel delay existing at the ramp location (t_d^{jk}). The freeway travel cost between ramp j and ramp k, C_f, equaled:

$$C_f(j,k) = \varphi_f \cdot \left(V_{jk} t_f^{jk} + \sum_{g=1}^{M_{jk}} q_{gj} t_d^{jk} \right) \tag{8}$$

where φ_f denoted the unit value of freeway travel time.

2.2. Construction Cost

The construction cost of the selected candidate ramps is the main constraint for most newly constructed ramps [34]. In this study, we used C_j to represent the construction cost of ramp j, and the value of C_j was calculated according to the actual situation. Therefore, the daily construction cost could be obtained from Equation (9):

$$C_s = \sum_{j=1}^{N} x_j \frac{C_j}{365\gamma_s} \tag{9}$$

where γ_s represents the service life of the freeway.

2.3. Safety Issue

The lane-change turbulence in the weaving segments around the ramps is significantly higher than that of basic freeway sections [11]. Newly constructed ramps may change the traffic flow on the freeway sections. As traffic flow rises, empirical investigations have discovered a lane-changing concentration problem, which can create flow breakdown and congestion [35,36]. Hence, we represented safety issues by the average frequency of lane-changing behaviors when vehicles entered or exited the freeway. The frequency of lane-changing behaviors in freeway section between ramp j and ramp k was obtained by Equation (10), which was fitted by simulation software:

$$H_{jk} = \mathrm{a} {V_{jk}}^2 + b V_{jk} + c \tag{10}$$

where $\mathrm{a} = -5 \times 10^{-7}$, $\mathrm{b} = 0.0016$, and $\mathrm{c} = -0.0233$ represent the fitting coefficient [37].

2.4. Model Development

This cost structure, therefore, defined the optimization problem by:

$[M]$:

$$minZ_1 = \sum_{j \in \overline{S}} [C_a(j,k) + C_f(j,k)] \tag{11}$$

$$minZ_2 = C_s(j) \tag{12}$$

subject to:

$$H_{jk} < H_{max} \tag{13}$$

$$L_{jk} \geq L_{min} \tag{14}$$

The first objective function (11) aimed to select the members of $\overline{S}$ to minimize the total travel cost, which included two cost terms: access cost and freeway travel cost. The second objective function (12) aimed to minimize the ramp construction cost. Constraint (13) incorporated the safety issue, which restricted the maximum frequency of lane changes in order to restrict the negative influence of lane-changing behaviors. Constraint (14) ensured that the ramp spacing met the requirement of minimum spacing, and L_{min} denoted the lower limit of the spacing.

3. Dynamic Programming Approach

Dynamic programming was first formalized by Bellman in 1996 [38]. It has been widely used to tackle transportation problems, such as backpack issues and shortest path problems [39]. In general, dynamic programming begins with a stage-and-state system. The optimization issue may be broken into a succession of simpler minimization problems in this way. Each stage is represented by state variables. Through recursive equations, the current value is decided by the values of the preceding stages, until the final stage is obtained. The last stage returns an optimal solution, according to Bellman's optimality principle [40]. Dynamic programming is well-known for its ability to solve constrained and non-linear problems while delivering globally optimal results. However, maintaining track of several solutions at the same time comes with a cost that rises exponentially with the number of objective functions [41–43]. Nevertheless, we were still able to acquire an exact solution in a short time with algorithmic design.

The freeway ramp placement problem was formulated as a multistage decision problem with two objectives. The classical ε-constraint method was used first to convert one of the objectives into a constraint. From the perspective of the efficient reduction of the total social cost, objective (11) was considered as the priority, with objective (12) formulated as a constraint. The model was then exactly solved by the dynamic programming approach, in which the multistage calculation process was carried out for each stage separately [44,45]. The method is described in detail below.

It is necessary to divide a problem into multiple sub-problems to apply dynamic programming. Each of these sub-problems is referred to as a "stage" [46]. Each stage is merely assumed to be associated with the stage before and after it. In this study, the discrete optimization problem could be separated by ramp. In dynamic programming, "state" is defined to represent the current status of a problem [47]. In this study, the state of each stage was defined as the placement from ramp j to ramp k.

The basis of computation in dynamic programming is the "recursive function", which is an optimization model that determines the optimum action of each state [48]. In this study, at an arbitrary stage, the objective was to obtain the lowest total travel cost from ramp j to its downstream ramp k. The stage variable was the index of the preceding ramp, which was the only information needed to optimize the rest of the ramp placement [49]. The definition of a recursive equation is defined as $f(j,k)$:

$$f(j,k) = \text{Lowest total travel } \cos\text{t for the freeway system from ramp } j \text{ to ramp } k \tag{15}$$

We used backward recursion, in which the computations proceeded from ramp $|N|$ to ramp 1. The decision process is illustrated in Figure 1. The recursive equation at first stage was expressed as:

$$f(j,N) = C_a(j,N) + C_f(j,N) \tag{16}$$

Next, the total expenses estimated in the first stage and the value of j were used as input data to calculate the stage immediately before it. We discussed the recursive equation for the next stage as Equation (17).

$$f(j,k) = min\left\{C_a(j,k) + C_f(j,k) + f(k,N)\right\} \tag{17}$$

In summary, this section elucidates the algorithm for solving the optimization model, and the approach developed is based on backward dynamic programming. In the first stage, we found a ramp that minimized the total travel cost from that ramp to the downstream one. This total cost was used as input data for the next stage. This process continued until the final stage. In each iteration, several candidate ramps were eliminated. Therefore, at the arbitrary stage, the corresponding function $f(j,k)$ was computed. The optimization process ended when $j = 1$ was determined. We could then obtain the optimal ramp locations from ramp 1 to ramp N, which was simply the optimal solution of Equation (11). A flowchart is provided to demonstrate this method (see Figure 2). We illustrate the model and the solution method using a case study in the next section.

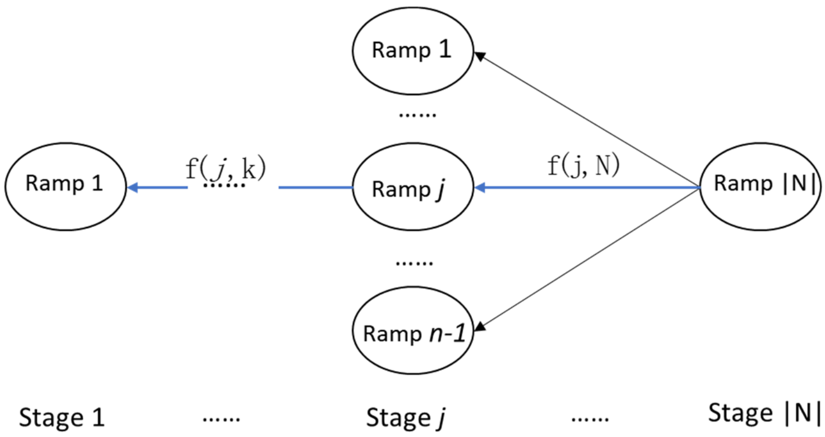


Figure 1. Decision process of a backward dynamic planning approach.

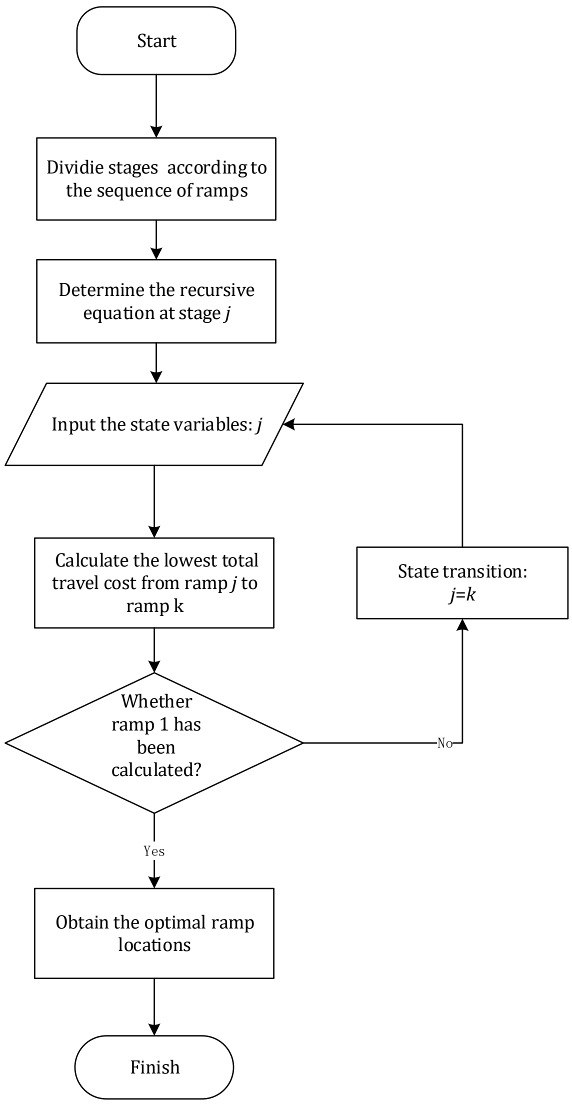
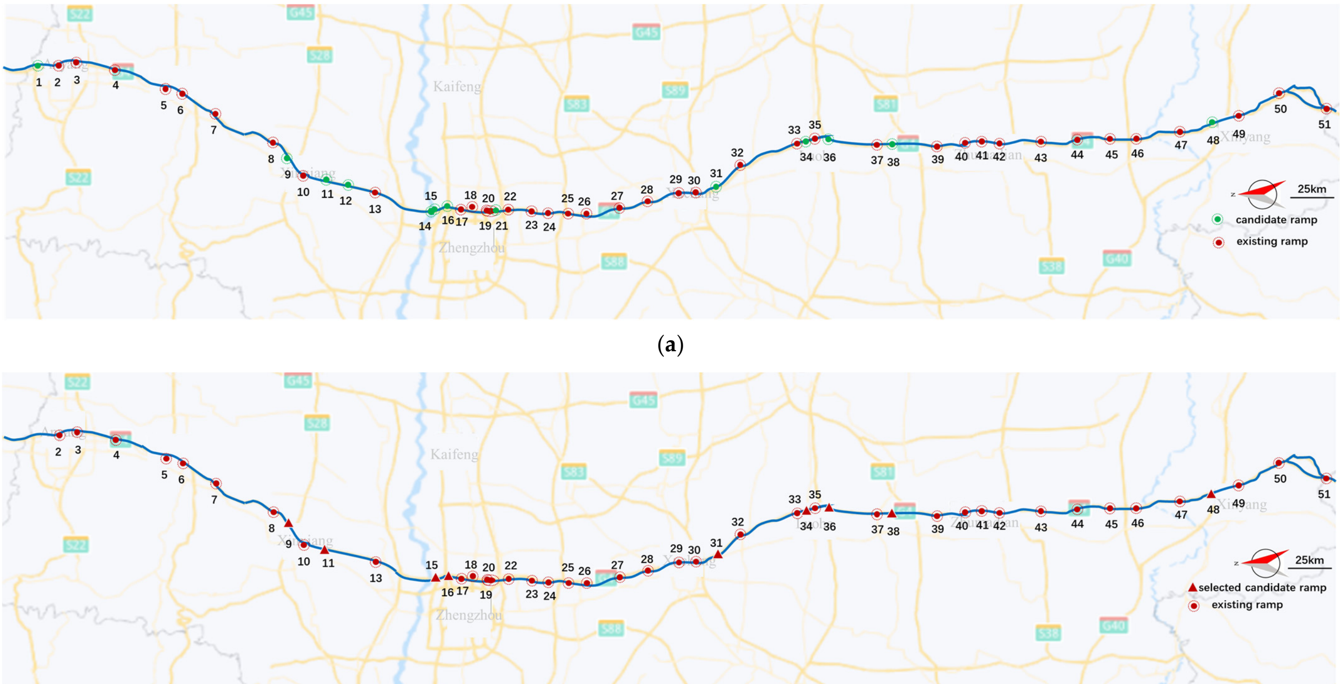


Figure 2. Flow chart of a dynamic planning approach.

4. Case Study

The proposed model and solution algorithm described in the previous sections were applied to a case study on the Beijing–Hong Kong–Macau Expressway within Henan Province, China. Henan Province is in the central area of P.R. China, with a population in 2021 of 98.83 million people and an area of 167,000 square kilometers. The Beijing–Hong Kong–Macao Expressway has a total length of 513 km within Henan Province, passing through eight prefecture-level cities in Henan Province. There are 38 existing ramps serving a total of 108 surrounding towns, which were the traffic regions in this case. The candidate ramps were selected at locations with aggregate demand nearby. In total, we selected 13 locations as candidate ramp sites. Figure 3a illustrates the sequential existing ramps and candidate ramps along the freeway.



(**a**)

(**b**)

Figure 3. Ramp placement on the Beijing–Hong Kong–Macao Expressway. (**a**) Existing placement. (**b**) Optimized placement.

Based on field investigations, we collected the travel demand of each traffic region and the distance between traffic regions and ramps. Table 2 uses ramp 1 as an example to present the data required for solving the model. Table 3 defines other parameters used in the numerical analysis. Hence, all parameters in objective function Equation (11) were obtained.

Table 2. An example of field survey data.

Ramp Number (j)	Service Area		
	Traffic Region Number (i)	d_{ij} (km)	Q_i (veh/h)
1	1	8	103
	2	2	84
	3	5.5	107
	4	5.4	232

Table 3. Parameter values.

Symbol	Description	Value
φ_a	Unit value of access cost	10
$\overline{v}_a$	Average access speed	50 km/h
c	Freeway capacity	3600 pcu/h
ε	Critical gap acceptance for vehicles entering or exiting the ramps	4 s
φ_f	Value of freeway travel cost	5
C_j	Construction cost of ramp j	$590,000
γ_s	Service life of the freeway	15 years

In this study, the Pareto optimal solutions of ramp locations were determined by the proposed dynamic programming algorithm. The solving process used the recursive equation $f(j,k)$ to calculate gradually backward from j = 51 to j = 1. Figure 4 illustrates each Pareto optimal solution and the Pareto optimal front. All the included non-dominant solutions can be seen as optimal to some extent, depending on the relative importance of the two objectives. In practice, these alternative solutions are beneficial for decision-makers since they can choose from several alternative freeway ramp locations that better meet the practical circumstances. One of the Pareto optimal solutions is presented in Figure 3b. The optimized result presented that the total travel cost of the location with eight newly constructed ramps (j = 9, 11, 15, 16, 31, 34, 36, 38, and 48) was the least.

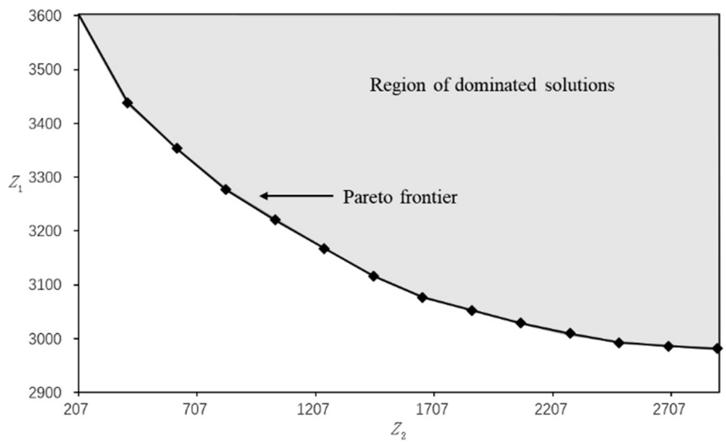


Figure 4. Objective values of Pareto optimal solutions.

For example, the freeway section from traffic region 29 to traffic region 32 has an existing ramp (j = 10) and a selected candidate ramp (j = 11) along this section in optimized placements (see Figure 5). In the condition of the existing ramp set, vehicles within the traffic regions (from i = 29 to i = 32) could only enter the freeway through ramp 10. However, the optimized placements allowed vehicles to access the freeway more efficiently by choosing a ramp closer to them (e.g., ramp 11). Thus, when the number of ramps increased, the accessibility of the freeway for vehicles within each traffic region increased significantly. In addition, we assumed that the total demand in each traffic region was constant in the optimization model. In the optimized ramp placement, the average demand attracted to each ramp decreased as the number of ramps increased. Additionally, both the safety and efficiency of ramps improved.

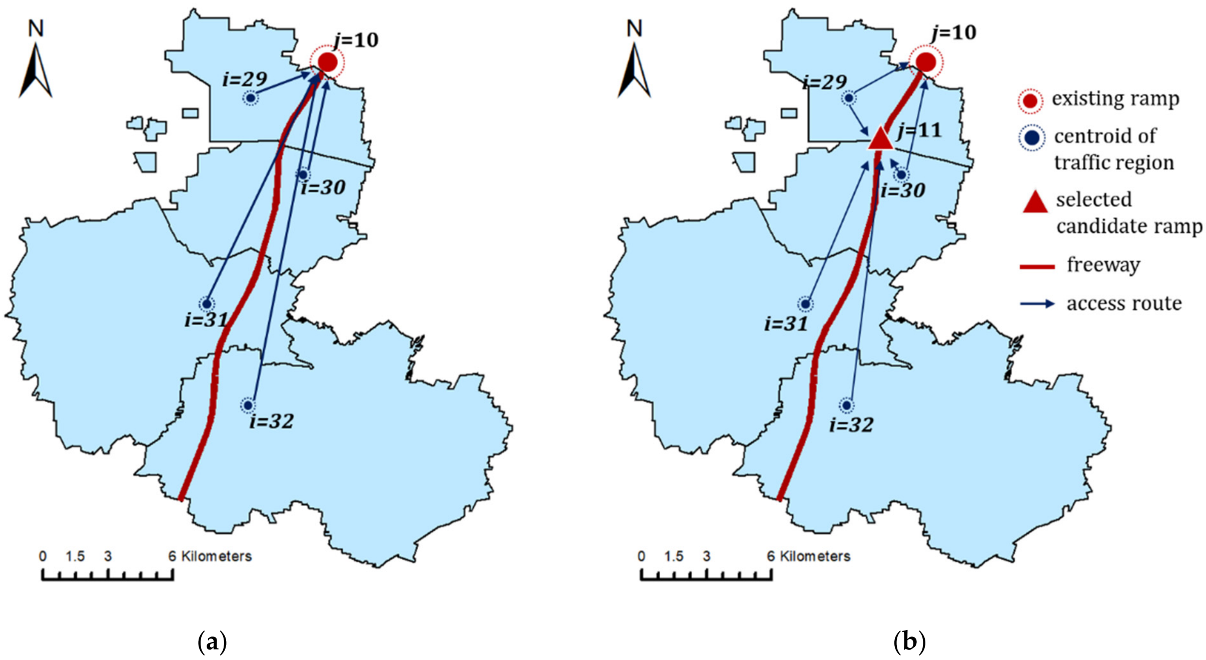


Figure 5. Access route change. (**a**) Existing placement. (**b**) Optimized placement.

In general, when compared with the existing ramp set, eight new ramps were added with the proposed solution method, enhancing the accessibility of the freeway for its service area. The additional ramps provided more route options for travelers in the service area and thus saved access time and travel time. Compared with the existing ramp locations, the optimized ramp placement reduced average access time per vehicle and freeway travel time per vehicle by 7.1% and 27.6%, respectively (see Table 4). Although the construction cost of the optimized placement was increased by approximately nine times, the total travel cost was reduced by 15.3%. Thus, the freeway ramp location optimization achieved a trade-off between construction cost and travel cost, effectively reducing the total social cost.

Table 4. Comparison of optimized locations and existing locations.

	Existing Locations	Optimized Locations
Total number of ramps	38	46
Average access time (h per vehicle)	0.169	0.157 (7% reduction)
Average freeway travel time (h per vehicle)	1.667	1.207 (27.6% reduction)
Total travel cost (USD)	3603	3052 (15.3% reduction)
Construction cost (USD)	2472	22,252

5. Conclusions

This study focused on the optimization of ramp locations along a freeway within a specific district. The accessibility of a freeway was enhanced by constructing new candidate ramps at suitable locations for residents to use the freeway service. Meanwhile, the ramp spacing needed a lower boundary limit to ensure freeway safety and operational efficiency. Considering both accessibility and efficiency, a bi-objective optimization model was formulated. Two objectives aimed to reduce the total social costs: the minimization of total travel cost and minimization of total construction cost. The frequency of lane changes around the ramps and minimum ramp spacing were limited to ensure that ramps were located in compliance with safety requirements. An exact solution method based upon the dynamic programming approach was developed to solve the proposed model. A case study of the Beijing–Hong Kong–Macao Expressway located within Henan Province, China, was conducted to demonstrate the applicability of the proposed model and solution method. The results of our study could be used as a guideline for designing freeway ramp placement.

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