Optimization of Opening Scheme of ETC/MTC Toll Lane Based on Cost and Benefit Analysis

Hao Zhang1,2, Cheng Cheng1, Changjian Zhang1, Jie He1*, Yang Xu1, Yokai Chen3, Qiong Hong4
1 School of Transportation, Southeast University, Nanjing, Jiangsu, 211189, China
2 School of Traffic Engineering, Huaiyin Institute of Technology, Huaian, Jiangsu, 223003, China
3 School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei, Anhui, 230009, China
4 Business School, Jiangsu Vocational College of Electronics and Information, Huaian, Jiangsu, 223003, China
*Corresponding author’s e-mail: hejie@seu.edu.cn

Abstract. In recent years, with the popularization of electronic toll collection systems (ETC), expressway toll stations in China have developed into a mixed toll form jointly deployed by ETC toll lanes and MTC toll lanes, presenting a development trend based on ETC toll lanes. Since the toll collection system has the important function of "credit repayment", the relationship between operation benefit and cost will become an important indicator for measuring the toll station system. Taking the minimum cost and the maximum benefit of the toll station under normal operating condition as the optimization goals, a multi-objective nonlinear optimization model is established within the seek for balance between cost and benefit, so as to obtain an open plan with better toll lanes. The Nanjing-Hangzhou toll station is used as an example to verify the model. Furthermore, based on the trend of the future traffic flow and the increase in the proportion of ETC vehicles, the distribution law of the optimal opening schemes of the toll lane under different traffic volumes and different traffic flow structures is analyzed, which provides experience support for the construction and operation of toll stations in the future.

1. Introduction
How to optimize the management and operation mode of highway toll stations and the reasonable opening and closing of the corresponding number of ETC/MTC lanes have a huge impact on reducing expressway spending, and improving the current status of "charging repay a loan". However, most of the calculation methods used in the past are based on the traditional manual charging method, which is no longer applicable to the status that the number of ETC vehicles has increased rapidly and the mixed setting mode of ETC and MTC has been enabled.

The current studies concerning the toll lanes of highway toll stations is still concentrated on "efficient driving", "safe driving" and "green driving"[1-2], with less discussion on toll station cost analysis. From the perspective of engineering construction, [3] discussed the construction plan of the toll station based on the goal of the largest toll collection. [4] comprehensively analysed the problem of ETC lane setting ratio from the perspective of engineering construction based on the queuing cost
and construction operation cost, and found that increasing the proportion of ETC lanes can significantly reduce the toll station cost. [5] put forward suggestions for improvement of toll station optimization in consideration of traffic efficiency analysis, taking into account the toll station construction cost. However, these studies have the following problems:

1) The previous studies mostly start from the engineering construction stage with the lack of research based on the management and operation stage.
2) Due to the gap in national conditions, foreign research results cannot be fully transplanted and applied.
3) The previous studies focus on a single goal while the optimization of management and operation needs comprehensive consideration from various aspects.

Based on these, this paper proposes to build a nonlinear multi-objective optimization model from cost analysis and benefit analysis, and discuss the opening modes of the ETC lane and MTC lane of the highway toll station in actual operation in different situations. Combined with the rising trend of the proportion of ETC vehicles in the future, the optimal number of toll lane openings under different traffic volumes and structure ratio of different traffic flows is calculated, and a scientific optimization calculation method for the lane opening scheme of highway toll stations is given.

2. Problem description
The main purpose of cost-benefit optimization is to reduce the costs of operators and users of toll stations while improving the utilization of resources. As the traffic volume changes, the opening ratio and quantity of ETC and MTC lane directly affect the labor cost of the toll station, operation cost, user delay cost and vehicle queue length.

- Too many lane openings will reduce the user delay costs but the labor and operating costs of the toll station will increase, resulting in idle tollgates, wasted resources and reduced toll station efficiency.
- The vehicles will queue up for service with a small number of lane openings, resulting in long delay time and high delay cost; too few lane openings may also lead to the collapse of the entire system due to excessive congestion.
- When the opening ratio of ETC lanes far exceeds the demand, the utilization rate of ETC lane will be reduced, resulting in the contradiction between the idle and waste of automatic toll lanes and the congestion of manual toll lanes.
- For the condition of excessive opening proportion of MTC lanes, the efficiency of ETC vehicles will be reduced, and the labor cost will increase with the increase of the opening number of MTC lanes.

In summary, the reasonable opening of toll lanes can reduce the operation and management costs of toll stations, effectively improve the efficiency of toll vehicles, improve the service level of toll stations, improve the driving experience of drivers, and achieve a "win-win" situation.

3. Model building
For multi-objective optimization problems, the solution is usually a set of non-inferior solutions—Pareto solution set. As a classic model in multi-objective optimization, Pareto is applicable to any objective and any function, without losing the information of the objective function and solution, and better guaranteeing the quality of the solution. But the optimal solution of the Pareto model is a set, which contains more than one optimal solution.

3.1. Cost analysis
In general, the cost of the toll station includes the operator's cost and the user's cost, and its specific composition is shown in Figure 1.
Fig. 1 The main cost composition of toll collection and payment by highway toll stations

For the operator of the toll station, the construction and fixed equipment costs have been determined after completion; for users, the installation of on-board ETC equipment is also a fixed one-time cost. Therefore, if these depreciation costs are not taken into account, the variable costs in the daily operation of the toll station are the labor cost of the toll station, the normal operation costs of facilities, the maintenance costs, and the time delay cost of the user, the quantitative analysis of these is as follows.

3.1.1. Labor cost $C_r$

Labor costs mainly include the wages of toll staff and other staff. Among them, the toll staff change with the opening number of toll lanes, while other staffs are relatively fixed according to the size of the toll station, which is not considered in the model. The calculation only considers the change of the tolled personnel. Calculated in the model by 30 days per month. Only changes in toll staff are taken into account when calculating. Each month is calculated at 30 days in the model.

$$C_r = \frac{C_a}{30 \times 24} \times r_a = \frac{C_a}{30 \times 24} \times n_m \times 3$$  \hspace{1cm} (1)

Where $C_r$ is the labor cost of toll station operation, yuan/h; $C_a$ is the average monthly salary of each toll staff, yuan/month; $r_a$ is the number of toll staff at the toll station, which is assumed to be equivalent to 3 times the number of lanes opened $n_m$.

3.1.2. Operation cost of facilities $C_s$

The operation cost of facilities is the cost of maintaining the normal operation of the toll station facilities. The electricity consumption cost is mainly considered here.

$$C_s = \frac{M_e}{30 \times 24} n_e + \frac{M_m}{30 \times 24} n_m$$  \hspace{1cm} (2)

Where $C_s$ is the operation cost of the toll station facilities, yuan/h; $n_e$ is the number of ETC toll lanes opened; $n_m$ is the number of MTC toll lanes opened; $M_e$ and $M_m$ are the average monthly electricity charges of ETC and MTC lanes, respectively, yuan/month.

3.1.3. Maintenance cost $C_w$

The maintenance cost is the fee for the toll station to carry out regular maintenance, repair and daily inspection of facilities.

$$C_w = \frac{W_e}{30 \times 24} n_e + \frac{W_m}{30 \times 24} n_m$$  \hspace{1cm} (3)

Where $C_w$ is the maintenance cost of the toll station, yuan/h; $W_e$ and $W_m$ are the monthly maintenance and repair cost of ETC lane and MTC lane, respectively, yuan/month.

3.1.4. Delay time cost $C_{\text{delay}}$

The delay time cost refers to the economic value lost by all personnel in the vehicle passing through the toll station during the delay time, which is determined by the average number of passengers carried by coach, the value of travel time per capita and the staying time (delay time) the vehicle stays in the
The value of travel time per capita is the economic value lost due to stay in a unit of time, determined by the income method and calculated by the average social wage in the survey area [4].

\[ V_{TOT} = \frac{W_{salary}}{30 \times 24} \]  

Where \( V_{TOT} \) is the per capita time value, yuan/(person \cdot h); \( W_{salary} \) is the per capita monthly income, yuan/month. The delay time cost is:

\[ C_{delay} = V_{TOT} \times L_{carry} \left( D_e \times Q_E + D_m \times Q_M \right) \]  

\[ D_e = \frac{1}{\mu_e - \lambda_e} = \frac{1}{\mu_e} \times \frac{Q_E}{n_e} = \frac{n_e \mu_e - Q_E}{n_e} \]  

\[ D_m = \frac{1}{\mu_m - \lambda_m} = \frac{1}{\mu_m} \times \frac{Q_M}{n_m} = \frac{n_m \mu_m - Q_M}{n_m} \]  

Where \( D_e \) is the average delay time of the ETC toll lane, h; \( D_m \) is the average delay time of the MTC lane, h; \( Q_E \) is the traffic volume of ETC toll lane within service hours, veh/h; \( Q_M \) is the traffic volume of MTC toll lane within service hours, veh/h; \( u_m \) is the average service rate of single lane in MTC lane, veh/h; \( u_e \) is the average service rate of single lane in ETC toll lane, veh/h; \( \lambda_e \) is the average arrival rate of single lane in ETC toll lane, veh/h; \( \lambda_m \) is the average arrival rate of single lane in MTC toll lane, veh/h; \( L_{carry} \) is the average number of passengers, people.

3.2. Theoretical benefit analysis

The benefit of highway toll station mainly reflects the occupation of lane resources by vehicles. Under the same traffic volume, the smaller the total number of lanes opened, the less wasted resources of lanes, employees, and equipment, and the better the theoretical benefit of the highway toll station. The ratio of traffic volume to the number of lanes, that is, the traffic volume per lane is directly used as the index to analyze the trend of benefit changes, which is restricted by the capacity of the toll station. The calculation formula can be abstracted as:

\[ B = \frac{Q_{total}}{n_{total}} = \frac{Q_E + Q_M}{n_e + n_m} \]  

Where \( Q_{total} \) is the total traffic volume within service hours; \( n_{total} \) is the number of toll lanes opened.

3.3. Comprehensive optimization model

Based on the above analysis, the multi-objective nonlinear comprehensive optimization model is constructed as follows:

3.3.1. Establishment of objective function

3.3.1.1. The objective equation based on maximum benefit:

\[ \text{Max } B = \text{Max} \left( \frac{Q_{total}}{n_{total}} \right) = f_1(Q_E, Q_M, n_e, n_m) \]
3.3.1.2. The objective equation based on the minimum cost:

\[
\begin{align*}
\text{Min } C &= C_s + C_e + C_v + C_{\text{car}} \\
&= C_s + C_e + C_v + C_{\text{car}} + (\frac{M_s}{30 \times 24} \times n_s + \frac{M_e}{30 \times 24} \times n_e + \frac{W_s}{30 \times 24} \times n_s + \frac{W_e}{30 \times 24} \times n_e) \\
&+ (\frac{W_{\text{car}}}{30 \times 24} \times L_{\text{car}} \times \left( \frac{1}{\mu_s} \times Q_s + \frac{1}{\mu_e} \times Q_e \right)) \\
&= C_s + C_e + C_v + C_{\text{car}} + (\frac{M_s}{30 \times 24} \times n_s + \frac{M_e}{30 \times 24} \times n_e + \frac{W_s}{30 \times 24} \times n_s + \frac{W_e}{30 \times 24} \times n_e) \\
&+ \frac{W_{\text{car}}}{30 \times 24} \times L_{\text{car}} \times \left( \frac{n_s}{n_s \times Q_s + Q_e} + \frac{n_e}{n_e \times Q_s + Q_e} \right)
\end{align*}
\]  

(10)

3.3.2. Establishment of constraints

The model should take into account the limitation and the capacity of toll lanes. Where \( n_{\text{emax}} \) is the total number of ETC toll lanes; \( n_{\text{mmax}} \) is the total number of MTC lanes.

\[
\begin{align*}
s.t. \quad & n_s \leq n_{\text{emax}} \\
& n_m \leq n_{\text{mmax}} \\
& n_s, n_m > 0 \\
& n_s, n_m \text{ are integers} \\
& n_s \mu_s > Q_s \\
& n_m \mu_m > Q_M
\end{align*}
\]  

(11)

3.3.3. Calculation and analysis methods

The calculation method divided into manual enumeration and computer programming should be determined based on the actual construction of the toll station and combined with the ratio \( k \) of ETC vehicles and MTC vehicles in the traffic flow. The enumeration method is effective on condition that the number of automatic toll lanes built in the toll station is small or the \( k \) value is small. However, when the number of automatic toll lanes increases and the \( k \) value increases to a certain proportion, the algorithm is solved by MATLAB software.

It can be judged that the maximum benefit model decreases monotonically with the increase of the number of lanes opened based on the form of the comprehensive optimization model, while the minimum cost model has a stagnation point—a local optimal solution. Therefore, based on the stagnation point of the minimum cost model when analyzing the calculation results, compare the advantages and disadvantages of the stagnation point and its neighborhood solutions, that is, the Pareto solution set is:

- The stagnation point of the minimum cost model.
- The neighborhood solutions that the cost is slightly higher than the stagnation point but the benefit is better than the stagnation point.

4. Illustrative example

Taking Nanjing-Hangzhou Toll Station as an object, the model is solved by combining the relevant traffic data extracted from the filmed video materials and the basic data of the relevant costs obtained from the on-site communication and inquiry. Parameter assignment for the model are Employee's salary (yuan), \( C_s = 8000 \); Average monthly electricity cost of ETC lane (yuan / month), \( M_s = 500 \); Average monthly electricity cost of MTC lanes (yuan / month), \( M_m = 1000 \); Average monthly maintenance facility fee of ETC lanes (yuan / month), \( W_s = 1200 \); Average monthly maintenance facility fee of MTC lanes (yuan / month), \( W_m = 1000 \); Average passenger capacity (person / vehicle), \( L_{\text{carry}} = 6 \); Per capita time value (yuan / h), \( V_{\text{VOT}} = 6.95 \); Total number of lanes, \( N = 12 \); The total number of ETC lanes (number), \( n_{\text{emax}} = 2 \); Passenger monthly income (yuan), \( W_{\text{salary}} = 5000 \); The capacity of ETC single lane (vehicles / h), \( u_s = 1200 \); The capacity of MTC single lane (vehicles / h), \( u_m = 275 \).
According to the survey data, when $Q_e=150, Q_M=810$, the ratio of ETC toll vehicles to MTC toll vehicles is $k=5:27$. Since the current situation is $n_{\text{max}}=2$, the Pareto solution set can be obtained directly by enumeration.

Table 1 Model solution results

| Program | Number of toll lanes opened | The total number of lanes opened | The ratio of ETC lanes to MTC lanes | Cost (yuan) | Benefit |
|---------|-----------------------------|---------------------------------|-----------------------------------|------------|---------|
|         | ETC | MTC | 4  | 0.33  | 6866.65  | 240.00  |
| 1       | 1   | 3   | 5  | 0.25  | 618.28   | 192.00  |
| 2       | 1   | 4   | 6  | 0.20  | 487.54   | 160.00  |
| 3       | 1   | 5   | 7  | 0.17  | 466.05   | 137.14  |
| 4       | 1   | 6   | 8  | 0.14  | 472.87   | 120.00  |
| 5       | 1   | 7   | 9  | 0.13  | 491.45   | 106.67  |
| 6       | 1   | 8   | 10 | 0.11  | 515.75   | 96.00   |
| 7       | 1   | 9   | 11 | 0.10  | 543.39   | 87.27   |

As Table 1, when $n_e=1, n_m=5$ in scheme 4, there is the lowest cost and the greatest benefit. Compared with scheme 4, scheme 3 has a slightly higher cost but a better benefit. That is, scheme 3 and scheme 4 are the preferred open mode of toll lanes under the current operating environment.

Taking into account the increasing trend of $k$ in the future, further hypothesis verification is carried out, keeping the remaining parameters unchanged, changing the total traffic volume $Q_{\text{total}}$ and the ratio $k$ of automatic toll vehicles and manual toll vehicles, and increasing $n_{\text{max}}$ to 10 to analyze the distribution law of Pareto solution set in different situations. The calculation results are as following:

1) The number of better ETC lanes opened increases with the increase of $Q_{\text{total}}$ and $k$, and the number of better MTC lanes opened decreases with the increase of $k$.

2) The cost of toll station increases with the increase of $Q_{\text{total}}$ in a certain value of $k$, and decreases with the increase of $k$ in a certain value of $Q_{\text{total}}$.

3) In terms of benefit analysis, when $k$ value is constant, the benefit of toll station first decreases and then increases with the increase of $Q_{\text{total}}$. When $Q_{\text{total}}$ value is constant, the benefit of toll station also shows an overall trend of decreasing first and then increasing with the increase of $k$ value. This is because the corresponding number of toll lanes constructed in the toll station is not enough to meet the quantity requirements of the better opening mode when the number of ETC or MTC in the traffic flow increases to a certain number.

5. Conclusion

This paper first makes a quantitative analysis of the cost and benefit of highway mixed toll stations in China supplemented by certain reasonable assumptions, and derives the calculation model of each part. Then a multi-objective optimization model is constructed based on satisfying basic traffic services. Next, taking Nanjing-Hangzhou Toll Station as an example, this paper calculates the better opening mode of Nanjing-Hangzhou Toll Station in which the toll lane is currently in operation. Finally, the Pareto solution set distribution law of the model under different traffic flows and $k$ values is obtained combined with the rising trend of the proportion of ETC vehicles in the future traffic flow. And the traffic flow structure suitable for the current toll station construction scale can be analyzed from the benefit distribution diagram.

Acknowledgments

This research is funded by NSFC (Grant No.51778141; 71871078; 71874067), Henan science and technology project (Grant No.182102310733), the “Six Industry Talent Peak Project” fund of Jiangsu Province (RFJW-049;JNB-115), the “Green and Blue Project” fund of Jiangsu Province (2017SJB1641), the Philosophy and Social Science fund for colleges in Jiangsu Province.
(2017SJB1641;2018SJA1649), the Natural Science Fund for Colleges in Jiangsu Province (17KJB58001).

References
[1] Cui Hongjun, Guo yiqing Li Xia, Li Lin. An Environment-friendly Control Method for Congestion Flow ahead of Expressway Toll Stations[J]. Journal of Southeast University(English Edition), 2016, 32(04):479-483.
[2] Zhu J, Yang T, Wang P, et al. Calculation of the Number of Toll Lanes in the Expressway Based on Multiple Payment[C]//2018 11th International Conference on Intelligent Computation Technology and Automation (ICICTA). IEEE, 2018: 278-281.
[3] Amorim M, Lobo A, Rodrigues C, et al. Optimal location of electronic toll gantries: The case of a Portuguese freeway[J]. Procedia-Social and Behavioral Sciences, 2014, 111: 880-889.
[4] Ji Yangbeibei, Zhou Jinfeng. Lane Allocation of Highway Toll Gate Based on Cost Analysis[J]. Journal of Chongqing Jiaotong University(Natural Science), 2018, 37(01):85-91.
[5] Wu S, Chen C, Zhang Y, et al. Optimizing the design of highway toll plaza[C]//2017 2nd International Conference on Education, Sports, Arts and Management Engineering (ICESAME 2017). Atlantis Press, 2017.