Research on Urban Environmental Impact of Different Traffic Trip Schemes Based on LCA

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Abstract. Life cycle assessment is an environmental management tool from a global perspective. It is used to evaluate the technology of products in their entire life cycle, that is, from the acquisition of raw materials, the production of products to the disposal of products. This article takes traffic transportation system in Harbin as the research object, adopts the life cycle assessment method to analyze the environmental impact of traffic travel system in Harbin through the analysis of energy use, the identification and quantification of environmental release, and the inventory data characterization. Based on the results of the study, the future transportation structure of Harbin is proposed.

1. Introduction

With the advancement of urbanization in China and the rapid development of urban economic level, residents’ demand for urban transportation is increasing day by day [1]. The rapid increase of the ownership of motor vehicles, especially private cars, have not only caused serious traffic jam, but also leads to various degrees of environmental problems such as haze and noise [2]. While, the traffic pollution is not only related to the huge traffic volume, but also related to the unreasonable traffic structure.

Domestic and foreign scholars have done a lot of in-depth research on the structure of traffic and the development of public transportation. For the new modes of transportation, the research on car sharing has been carried out earlier in foreign countries, while the domestic use of e-commerce and mobile payment technology has led to a more in-depth study of shared bicycles; and the research on the environmental impact of transport trips is mainly limited to Monitoring of atmospheric and noise pollution generated by motor vehicles and establishment of small-scale model simulations and predictions.

As an environmental management method, life cycle assessment has developed rapidly both at home and abroad. However, there are only a few relevant researches in the area of traffic and transportation. This situation is mainly due to the rise of the method from the industrial production field and the gradual application to other fields. The framework, database, evaluation method construction and case application of the method need a long-term development and improvement process.

At present, the research on environmental impacts of transport based on life cycle assessment method is almost blank at home and abroad. Most of them stay in the monitoring of atmospheric and...
noise pollution generated by motor vehicles or establishing models to carry out small-scale emission of specific pollutants emitted by motor vehicles. Based on the current research status at home and abroad, it can be seen that there are still many chances for exploration in the life cycle assessment of the transportation sector in terms of research content, research field, and research level.

The predecessors have conducted a lot of research and achieved remarkable results with respect to the statistical analysis of traffic trip structure and comfort from the point of view of building a model and the forecast analysis of future traffic development. However, establishing the LEAP model to estimate the impact of different traffic trips on energy and the environment has regional limitations. Therefore, it is necessary to quantify the global environmental impact of different urban mobility programs from the perspective of the full life cycle.

2. Life cycle assessment theory

2.1. Life cycle assessment definition
LCA refers to the compilation and evaluation of the input, output, and potential environmental impacts of a product system's life cycle. It is a technology and methods used to evaluate environmental impact of products throughout their entire life cycle, from the acquisition of raw materials, the production of products, to after-using.

2.2. Life Cycle Assessment Steps
On the basis of the life cycle assessment framework defined in ISO 14040 [3], Fan Qingxin et al. [4] made a detailed review of the framework of the product life cycle assessment, as shown in Figure 1. In general, life cycle assessment includes the following steps. First of all, it is necessary to clarify the object of study and the purpose of research, and to determine a reasonable and appropriate system boundary. Then, we objectively quantify the resources and energy needed for the entire system and the resulting environmental release. After that, based on the resource consumption data and environmental release data provided in the inventory analysis, the environmental impact caused by the product or service is predicted and evaluated. Finally, explain the results of life cycle assessment, identify the characteristics of the problem, assess the credibility and make recommendations. The evaluation of credibility can be performed at any stage of the evaluation according to the specific situation, so as to optimize and control the data quality until the requirements are met [5].

![Figure 1. Life cycle assessment framework.](image-url)
2.3. Introduction to Life Cycle Assessment Software GaBi
GaBi is a life-cycle-assessment software developed by PE-INTERNATIONAL of Germany for the sustainable development of products. The software has a rich environmental database. The data is mainly from Ecoinvent, PE-GaBi, PlasticsEurope and Buwal. The evaluation methods conclude CML, EI, EDIP and UBP. The software version used in this article is GaBi Education 6.0.

3. Life Cycle Assessment of Traffic Trip Schemes System in Harbin

3.1. Introduction of Traffic trip schemes in Harbin
The research object of this article is the traffic situation in Harbin. Harbin is the capital of Heilongjiang Province, sub-provincial city, and megalopolis. It is the traffic, political, economic, cultural, and financial center of the northeastern part of China. It is also a megacity with the largest territorial jurisdiction in mainland China and the third largest household registration population. It is located in the northeastern plain of Northeast China. As of 2015, Harbin has a total area of 53,100 square kilometers and a city area of 10,198 square kilometers. It administers 9 municipal districts and 7 counties, and administers 2 county-level cities with a population of 106.65 million. This article only studies the traffic conditions in Harbin, which are densely populated, with similar traffic development time, in Daoli District, Nangang District, Xiangfang District, Daowai District, Pingfang District and Songbei District, regardless of Hulan District, Acheng District and Shuangcheng District.

After studying the relevant research and carrying out field surveys, the relevant data on obtaining traffic conditions in the Harbin urban area are as follows.

3.1.1. Population. According to the “Summary of the Sixth National Population Census” issued by the National Bureau of Statistics of the People's Republic of China in 2010 and the “Harbin City Overview 2016” issued by the Harbin Municipal Bureau of Statistics in 2016, the permanent population of Harbin City is 10.636 million people, and the total registered population is 9.614 million people, of which the population in the municipal district is 5.487 million, the urban population is 4.643 million, and the population in the main urban area is 4.518 million, and the natural population growth is -0.17‰.

3.1.2. Total transportation volume. Total transportation volume refers to the sum of all travel activities that residents make to meet various living needs. The annual travel volume is considered in this study. The total transportation volume is calculated as follows:

The total transportation volume = "Average number of trips per person × Urban population"

According to “The Harbin Comprehensive Transportation Development 12th Five-Year Plan”, the average number of trips per capita in Harbin City in 2015 was 2.30 person/day. Since the frequency of urban census is once every three years, the population is calculated according to the values in Table 2-1. The current value of Harbin's total transportation volume is 103,904,400 people/day and 379,249.6 million people/year.

3.1.3. The sharing rate of each mode of transport. The sharing rate of each mode of transport refers to the proportion of the volume of trips by different modes of travel to the total trip volume, which reflects the trip structure of the city. By consulting the “Notice of the Harbin Municipal People's Government on Printing and Distributing the Outline of the Thirteenth Five-Year Plan for National Economic and Social Development of Harbin” and the “Report of the People’s Government of Heilongjiang Province on the Priority Development of Public Transport in the City”, the sharing rate of various traffic travels in Harbin were obtained. The value of the share rate of the mode is shown in Figure 2.
3.1.4. The average travel distance of each mode of transportation. The average travel distance of each mode of transport refers to the average distance each time a city resident travels using each mode of transportation.

(1) Ground Public Transportation

In 2015, Hebei Institute of Technology used a floating car to investigate the bus travel data in Harbin, and carried out follow-up surveys on the starting and ending points of the city’s bus trips, trips, car time, and walking time, with a sample size of about 96,000. After expanding the sample size, 15223 OD pairs and 174835 trips were formed.

The following formula was used to calculate the average travel distance of ground public transport travel in Harbin for the 2015 Harbin Public Transport OD Matrix data.

$$D = \sum_{i}^{1-n} \sum_{j}^{1-n} t_{ij} \times d_{ij}$$

$$T = \sum_{i}^{1-n} \sum_{j}^{1-n} t_{ij}$$

$$d = \frac{D}{T}$$

$D$ —— Total travel distance

$T$ —— Total trips

$t_{ij}$ —— Transportation volume from zone i to zone j

$d_{ij}$ —— Travel distance from Zone i to Zone j

$i,j$ —— Transportation zone

From this calculation, the average travel distance of ground public transport in Harbin is 6.8km.

(2) Taxi

Refer to “Characteristic Analysis of Taxi Passengers Traveling in Harbin" [6] for statistics on travel distances for taxis in Harbin for a period of one month. The statistical results obtained are shown in Figure 3.

As shown in Figure 3, among the people who choose to travel by taxi, the number of people with different travel distances has a normal distribution, and the average travel distance is 6.1 km.

Figure 2. The current traffic sharing rate of the status quo in Harbin
3. Private cars
The average distance traveled by private cars is based on field research. In January 2017, this study conducted a household survey in six communities with typical urban morphological characteristics in Harbin City. On average, there are about 100 households in each community, with a total of 864 samples. The survey questionnaire mainly includes the basic situation of the family, the purpose of the trip, the mode of travel, and the distance to travel. According to the survey results, a total of 238 people own private cars. By calculating the weighted average travel distance per person and number of trips, the average travel distance of private cars is 11.2 kilometers.

4. Subway
Since the Harbin Metro Lines 1 and 3 have not yet been completed and the operation time is relatively short, the reference to Shenzhen, of which urban area scale is equivalent and three subway lines were constructed in 2010. The per-person travel distance by rail in Shenzhen is 7km.

5. Walking
Since walking does not consume any energy and does not produce pollutants, it does not affect the final calculation results. There is no need to investigate and analyze the average distance traveled by walking.

3.1.5. Average passenger capacity. Average passenger capacity refers to the average number of passengers carried by a mode of transportation. The calculation method is as follows:

\[
C = \frac{T_n}{N_v \times n \times 365 \times F_L}
\]

(1) Ground Public Transportation
For ground public transportation, the following calculation method is used to determine the average passenger capacity.

\[
C = \frac{T_n}{N_v \times n \times 365 \times F_L}
\]

- \(C\) —— Average carrying capacity
- \(T_n\) —— Annual bus traffic
- \(N_v\) —— Number of operating vehicles
- \(n\) —— Daily operating times
- \(F_L\) —— Full load rate

Figure 3. The current traffic sharing rate of the status quo in Harbin
According to the statistics of Harbin Bureau of Statistics, there were 7,408 vehicles in operation in 2015. The annual bus passenger traffic reached 1.34 billion passengers, and the average full-load rate was 45.3%. The bus operating time of each line was calculated from 05:00 to 21:00. The number of daily operations is about 5 times/day, and the average number of passengers is 45 people.

(2) Subway
For rail transit, the following calculation method is used to determine the average passenger capacity.

\[ C = \frac{T_p \times n}{N_v \times 365} \]

| \( C \) | Average carrying capacity |
| \( T_p \) | Annual subway traffic |
| \( N_v \) | The number of subway trains operating |
| \( n \) | Daily operating times |

Through on-site research, it is known that in 2015, Harbin Metro Line 1 has a 57,789,000 person-times passenger traffic volume. Operating hours are from 06:00 to 21:30, 17 stations in total, and about 35 minutes per shift. The peak driving interval is 5 minutes and 30 seconds, 13 lines are operating; the normal period driving interval 7 minutes and 30 seconds, 10 lines are operating; low peak driving interval is 10 minutes, 7 lines are operating, the operation detail is in Table 1. Therefore, the number of daily operations is about 53 times per day, and the average number of passengers is 600.

| Period               | Time            | Subway operation cycle/min | Operating times per day | Total daily turnover |
|----------------------|-----------------|----------------------------|-------------------------|---------------------|
| The peak driving interval | 7:00——9:00     | 40.5                       | 17.78                   |                     |
|                      | 16:00——18:00   |                            |                         |                     |
|                      | 9:00——16:00    |                            |                         |                     |
| the normal period    | 18:00——20:00   | 42.5                       | 32.47                   | 53                  |
| low peak driving     | 6:00——7:00     | 45                         | 2.67                    |                     |
| interval             | 20:00——21:00   |                            |                         |                     |

(3) Taxi
According to the study and statistical results of professional advisory board in Harbin, which focus on taxi industry management system in Harbin, the average full-load rate of taxis in Harbin is 60%, and the average passenger capacity is 2.4 passengers.

Private car
According to the household survey, the average passenger capacity of private cars in Harbin is 1.42, and the full load rate is 35.5%.

(4) Bicycle and Walking
According to common sense, the average pedestrian capacity of pedestrians is one, and the full load rate is 100%.

3.1.6. Average energy consumption factor. The average energy consumption factor refers to the amount of fossil fuel or electric energy that is consumed by the distance traveled by the unit.

(1) Ground Public Transportation
The number of buses, details of operations, and corresponding energy consumption in Harbin were investigated in detail. The results are shown in Table 2. According to the field investigation in this paper, the main energy source of buses in Harbin is natural gas, and only NO.83 and NO.203 buses will use electric. To simplify the calculation, the electricity consumption is partially ignored and only the compressed natural gas is calculated.

**Table 2. Harbin City Bus Energy Consumption Data**

| Number of vehicles | Operating Period | Average round trip mileage /km | Average daily round trip times /time | Average daily consumption of natural gas /m³ | Natural gas consumption (L/km) |
|-------------------|------------------|-------------------------------|------------------------------------|------------------------------------------|-------------------------------|
| 7500              | 6:00—21:00       | 50                            | 6                                  | 198                                      | 657.89                        |

(2) Subway
Since the Harbin Metro lines 1 and 3 have not yet been completed and the operation time is quite short, there is no statistical data. Therefore, referring to the data of the Beijing Subway, the subway consumes 4 kW•h/km.

(3) Private car
The average fuel consumption of private cars refers to domestic research, the private car's fuel economy is 11.03km/L, that means, the average fuel consumption of private cars is 0.09L/km [60].

(4) Taxi
Through on-site interviews and surveys with 12 taxi company chiefs such as Harbin Taxi Co. Ltd., we learned that the current taxi energy power in Harbin is mainly CNG (Compressed Natural Gas), and only when it is started, consumption of gasoline is required. The specific fuel consumption data for taxis is shown in Table 3.

**Table 3. Harbin taxi fuel consumption table**

| Average daily mileage /km | CNG prices(yuan/m³) | Gasoline prices (yuan/L) | CNG consumption (m³/ day) | Gasoline consumption (L/day) | Winter | Summer |
|--------------------------|---------------------|--------------------------|---------------------------|-----------------------------|--------|--------|
| 400                      | 3.8                 | 6.7                      | 42.11                     | 0.50                        | 0.25   |        |

It can be seen from Table 3 that the natural gas consumption factor for taxis in Harbin is 105.28 L/km. The weighted average of gasoline consumption in winter and gasoline consumption in summer in Harbin can be obtained. The gasoline consumption factor for taxis in Harbin is $9.375 \times 10^{-4}$ L.

3.2. Define system boundary determination
The system boundary is defined in this study as the analysis of the life cycle inventory of Harbin traffic from the start of energy extraction and processing to the termination of motor vehicle energy consumption. It involves three stages of energy extraction and processing, energy conversion and energy consumption. The energy extraction and processing stage mainly considers the environmental impacts of the mining, processing, selection, treatment and refining processes of coal, oil and natural gas. Due to the small impact and the difficulty of data acquisition, the production of related plant equipment and tools is not considered. The main energy consumption in the energy conversion phase is the power source of subway, that is, the thermal power generation process; the energy consumption phase mainly includes the environmental impact of fuel combustion release during the operation of motor vehicles. The system boundary is shown in Figure 4.
3.3. Define functional units
The purpose of defining functional units is to provide a reference for input and output data related to the traffic system in Harbin. This article takes account of all the environmental impacts of Harbin's transportation system energy extraction and processing, energy conversion, and energy consumption. The total annual travel volume in 2015 is 379,249,000 person-times as a functional unit, i.e. accounting for annual environmental impact of 379,249,600 person-times in total per year under current conditions.

3.4. Analysis of LEAP Model Construction and Energy Consumption
The Harbin traffic travel energy consumption model is based on the LEAP model.

The Long-range Energy Alternatives Planning System (LEAP) is a bottom-up energy accounting tool based on scenario analysis developed jointly by the Stockholm Environment Institute and Boston University, USA[7]. The LEAP model framework for the energy consumption of transportation travel in Harbin studied in this paper is shown in Figure 5.
Figure 5. The LEAP model framework for energy consumption of transportation travel in Harbin

Calculate the amount of ownership, activity level and mileage of each mode of travel, calculate the fuel consumption and power consumption of each mode of travel, and then calculate the total energy consumption of urban traffic.

\[
E_c = \sum_{i,j,k} \frac{T \times P_{ij} \times D_{ij} \times Fe_{ij}}{O_{ij}}
\]

- \(E_c\) — Transportation Energy Consumption in Harbin
- \(T\) — Total trip volume in Harbin
- \(P_{ij}\) — The sharing rate of each mode of transportation
- \(D_{ij}\) — Travel distances by all modes of transportation
- \(O_{ij}\) — Full load rate
- \(Fe_{ij}\) — Energy consumption factors of all modes of transportation
- \(i\) — Various modes of transportation, such as subways, buses, taxis, etc.
- \(J\) — Different types of energy consumption, such as gasoline, natural gas, electricity, etc.

According to the collection and arrangement of traffic travel status data in the above-mentioned article, we can see the traffic energy consumption status of traffic in Harbin. The specific conditions are shown in Table 4.
3.5. LCA model construction and inventory analysis

Life cycle inventory analysis is an objective quantification of the input process and environmental release of resources and energy in the entire life cycle of the entire Harbin traffic system. This article uses Gabi 6.0 software to build the LCA model of the Harbin traffic travel system and obtain the environmental release list of its entire life cycle, as shown in Figure 6.

| Energy type | Unit     | Consumption volume/year |
|-------------|----------|-------------------------|
| CNG         | m$^3$    | 2.3316×10$^8$           |
| Electricity | kW·h     | 7.0793×10$^6$           |
| Gasoline    | m$^3$    | 2.1600×10$^5$           |

Table 4. Transportation Energy Consumption in Harbin

![Figure 6. The schematic diagram of GABI model](image)

Take the thermal power generation process as an example to briefly describe its accounting process. Assuming that 1kW·h electricity is consumed, the environmental emissions of CO$_2$, SO$_2$, fly ash, etc. emitted by thermal power 1kW·h can be found in the background data. The multiplication of these substances with the consumption of electricity can lead to the environmental release of the electrical energy required by the system.

After the calculation is completed, the quantitative results of the environmental release of the traffic system of Harbin City under the current conditions are obtained, and the environment release totals 1.45×10$^{10}$kg. The environmental release list is shown in Table 5.
Table 5. Traffic Travel System Pollution Release List in Harbin (Unit: kg)

| Category       | Substance/element | Total amount | Energy extraction stage | Energy conversion stage | Energy consumption stage |
|----------------|-------------------|--------------|-------------------------|-------------------------|--------------------------|
| Atmospheric pollutant | CO₂               | 7.70×10⁸    | 7.94×10⁷                | 7.71×10⁶                | 6.83×10⁸                 |
|                 | SO₂               | 4.77×10⁶    | 4.30×10⁶                | 7.06×10⁴                | 4.12×10⁵                 |
|                 | NOx               | 5.20×10⁶    | 1.76×10⁵                | 2.47×10⁴                | 5.00×10⁵                 |
|                 | NMVOC             | 1.49×10⁵    | 1.42×10⁵                | 1.87×10²                | 6.76×10³                 |
|                 | THC               | 4.03×10⁶    | 1.80×10⁵                | 0                       | 3.85×10⁶                 |
|                 | PM₁₀              | 9.41×10³    | 8.20×10²                | 1.23×10¹                | 7.36×10³                 |
|                 | PM₂.₅             | 2.76×10³    | 1.53×10²                | 3.97×10¹                | 2.21×10³                 |
|                 | BOD               | 2.73×10³    | 2.72×10¹                | 4.42×10⁰                | 5.58×10⁰                 |
|                 | COD               | 5.95×10⁴    | 5.86×10⁴                | 8.35×10¹                | 7.50×10¹                 |
|                 | TN                | 4.14×10¹    | 3.49×10⁴                | 8.01×10¹                | 1.90×10⁰                 |
| Water pollutants | Cr                | 1.57×10³    | 2.03×10³                | 0                       | 0                        |
|                 | Cu                | 2.85×10²    | 2.85×10²                | 0                       | 0                        |
|                 | Pb                | 1.90×10²    | 1.90×10²                | 0                       | 0                        |
|                 | Fe                | 9.12×10³    | 9.12×10³                | 0                       | 0                        |
| Total           |                   | 1.45×10¹⁰  | 1.37×10¹⁰               | 7.81×10⁶                | 7.54×10⁸                 |

Based on the results of the inventory analysis, through the use of formula (1) with the weighting factors of each type of environmental impact type, the characterization results of the environmental impact of the current traffic system in Harbin are calculated. Based on the energy extraction and processing stage, the energy conversion phase, the energy consumption phase, and the characterization data of the system boundary, the research set out the characterization values of various stages in the system for different types of environmental impact, as shown in Table 6. In addition, seven kinds of pie charts of environmental impact potential were drawn to more intuitively characterize the relative contributions of Harbin's traffic trip system to environmental impact potential, as shown in Figure 6 to Figure 12.

\[
EP(j) = \sum EP(j)_i = \sum [Q_i(j) \times EF(j)_i]
\]  

- EP(j) —— Characterization of the jth environmental impact of a product or service system;
- EP(j)i —— Characteristic value of environmental impact of the ith emission material in the jth;
- EF(j)i —— Correlation coefficient of environmental impact of the ith emission material in the Jth;
- Q_i —— Emissions of the ith substance.
Table 6. Traffic Travel System Characterization Results in Harbin

| Environmental impact category | Total amount | Energy extraction Processing stage | energy Conversion stage | energy Consumption stage |
|-------------------------------|--------------|------------------------------------|-------------------------|-------------------------|
| ADP fossil(MJ)                | 6.62×10⁹     | 6.37×10⁶                           | 8.01×10⁷                | 1.69×10⁸                |
| GWP(kgCO₂)                    | 7.90×10⁸     | 9.93×10⁷                           | 7.71×10⁶                | 6.83×10⁸                |
| AP(kgSO₂)                     | 8.34×10⁶     | 5.25×10⁶                           | 1.00×10⁵                | 2.99×10⁶                |
| EP(kgPO₄³⁻)                   | 7.11×10⁵     | 5.80×10⁴                           | 3.22×10³                | 6.50×10⁵                |
| HTP(kgDCB)                    | 2.10×10⁸     | 2.01×10⁸                           | 2.62×10⁶                | 6.19×10⁶                |
| POCP(kg C₂H₄)                 | 2.56×10⁶     | 2.96×10⁵                           | 4.13×10³                | 2.26×10⁶                |
| TETP(kgDCB)                   | 6.82×10⁴     | 5.01×10⁴                           | 1.16×10³                | 6.52×10³                |

Figure 7. -1 Fossil energy consumption potential

Figure 7. -2 Global warming potential

Figure 7. -3 Acidification potential

Figure 7. -4 Eutrophication potential
From Table 5-9, we can see that in the current stage of traffic trip system in Harbin, the stage that contributes most to the environmental impact is the energy extraction and processing stage, and it is the largest percentage of the four impact categories of ADP fossil, HTP, TETP, and AP, all exceeding 60%, were 96%, 96%, 73%, and 63% respectively, and the EP accounted for the smallest proportion, 8%. Since the greenhouse gases associated with global warming and the PAN-related pollutants associated with photochemical ozone synthesis are relatively small during the energy extraction and processing phase, the contribution to GWP and POCP is far less than the energy consumption phase. The proportions are 13% and 12% respectively. For energy consumption stages, the greenhouse gases CO₂, N₂O, and CH₄, which are not completely combusted, due to the combustion of fuel are the most important reasons for the global warming potential of the Harbin traffic system. Therefore, the energy consumption stage contributes as much as 86% in the GWP. In addition, due to the large amount of NOₓ emissions in the energy-consuming phase, the contribution in EP and POCP also exceeded 80%, accounting for 91% and 88% respectively. The phase that has the least contribution to the environmental impact is the energy conversion phase. It has almost no contribution to GWP, EP, AP, POCP, and HTP, and the percentages are less than 1%. Its contribution to TETP and ADP fossil is relatively high, accounting for 17% and 3% respectively.

4. Conclusion
This article adopts the life cycle assessment method, takes the Harbin traffic transportation system as the research object, to calculate the energy consumption of the current traffic system of Harbin and the environmental impact of the global large-scale environment. Compared to the energy consumption phase, the extraction and processing stages of natural gas, coal, and gasoline also have a greater
impact on the environment. It is the largest percentage of the four impact categories of ADP fossil, HTP, TETP, and AP, all exceeding 60%, were 96%, 96%, 73%, and 63% respectively.

Therefore, under the condition that traffic volume is increasing day by day, optimizing the traffic structure will be the key to energy conservation and emission reduction at the traffic level. For Harbin, first of all, vigorously develop natural gas-electric power hybrid public transport, and then actively promote the use of zero-emission electricity as a driving force for the construction of subways, and encourage Internet-based car sharing and bicycle travel and walking. They are all effective measure to reduce environmental impact.

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