Train Headway Models and Carrying Capacity of Super-Speed Maglev System∗

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Train headway models are established by analyzing the operation of the Transrapid Super-speed Maglev System (TSMS). The variation in the minimum allowable headway for trains of different speeds and consists is studied under various operational constraints. A potential Beijing–Shanghai Maglev line is used as an illustration to undertake capacity analyses with the model and methods. The example shows that the headway models for analyzing the carrying capacity of Maglev systems are very useful for the configurational design of this new transport system.

Key Words: Maglev, Headway, Modeling, Line Capacity

1. Introduction

The super-speed maglev system Transrapid is a guideway-bound transportation system for passengers and high-value cargo traffic. It is one of the most significant innovations in guided ground transport technology since the construction of the first railroad. The non-contact technology of TSMS—controlled magnetics are used instead of mechanical components—overcomes for the first time the limitations of wheel-on-rail technology. In operation, Transrapid is faster and quieter than high speed rail systems. It is virtually impossible to derail and is comfortable at all speeds. The guideway of Transrapid requires less space and can be flexibly aligned to accommodate local topographic variations. However, its cost-effectiveness has yet to be proven.

The Transrapid system has been developed over 35 years(1)–(5). The first commercial Maglev line has been built at Pudong in Shanghai, China with German technology. Also, the techno-economic attributes of Maglev relative to high-speed wheel-on-rail technology are being evaluated for what is likely to be the first high-speed inter-city line in China (Beijing–Shanghai). Train headway is important both for safety and carrying capacity when undertaking operational analysis. Headway models of wheel-on-rail systems have been studied for different control schemes, such as fixed block and moving block(6). However, no detailed headway models for operational analysis of Maglev systems have yet been reported.

The contents of this paper are as follows. First, TSMS operation is analyzed and train following headway models are set up. Second, the variation of minimum allowable headway for trains of different consists is studied. Third, carrying capacity of a Maglev system is calculated. The example of a Beijing–Shanghai Maglev line is used for capacity analysis with the model and methods. Lastly, the main conclusions of this paper are presented.

2. Dynamic Train Headway Models

2.1 Minimum headway criteria

The first criterion for minimum headway of any guided ground transportation system is that if a vehicle should stop suddenly for whatever reason, the following vehicle must be able to come to a safe stop at an acceptable deceleration before reaching the location of the immobilized vehicle. For the case of a vehicle with a cruising speed of 450 km/h, for example, the distance and time to stop at a deceleration of 0.15 g are 5.2 km and 83 seconds, respectively. The minimum headway is, of course, speed dependent, and other factors are likely to dictate a higher operational minimum headway. We now consider TSMS.

2.2 Train following moving headway models for TSMS

In the single-sided mode, one side of each power substation supplies energy to a section of the distributed linear synchronous motor (LSM) armature in the guideway, while the adjacent sections are un-energised. The
minimum separation of two Maglev trains is thus two LSM sections (see Fig. 1). For the double-sided mode, each power-substation can energise two sequential sections, and the minimum separation of two Maglev trains becomes just one section of the propulsion system (see Fig. 2). Note that each section of the propulsion system may be subdivided and each sub-section switched sequentially to increase motor efficiency.

In order to assure safety with the two configurations of energy supplying system, the minimum separation \( L_z \) between Transrapid trains should meet Eqs. (1) and (3), respectively. The time interval (headway) \( I_z \) should meet Eqs. (2) and (4).

\[
L_z = L_{c} + L_{d,c} + L_{q} + 0.5L_{d,q} + 0.5L_{d,h} + 2L_{s}
\]
\[
L_z = L_{a} + L_{c,h} + L_{q} + 0.5L_{d,q} + 0.5L_{d,h} + 2L_{s}
\]
\[
I_z = t_u + \frac{v_0}{\bar{a}}
\]
\[
I_z = L_a + L_{c,h} + L_{q} + 0.5L_{d,q} + 0.5L_{d,h} + L_s
\]
\[
I_z = t_i + \frac{L_{c} + L_{d,c} + L_{q} + 0.5L_{d,q} + 0.5L_{d,h} + L_s}{v_0}
\]

where \( L_{c} \) and \( t_i \) are the distance and time advanced by the following train when the leading train transmits information to the following train, via the central control system. \( L_{d,c} \) is the dynamic braking distance of the following train. \( L_{d,q} \) and \( L_{d,h} \) are the lengths of the leading and following trains, respectively. \( v_0 \) is the average velocity of the following train in \( L_{a} \). \( L_{q} \) is a safety distance, and \( L_s \) is the separation of adjacent power sub-stations.

The train dynamic headway models of Eqs. (1)–(4) are basic conditions for assuring safe train operation. In order to maximize line capacity, the following train should maintain minimum dynamic headway. If headway is increased, the leading train will not influence the following train in normal operational conditions. This minimum headway will be used as the dynamic separation of two trains in the following analysis.

2.3 Departing, arrival headway models

When the trains pass an off-line station and do not stop, the minimum headway is similar to the train following moving headway as determined by Eqs. (1)–(4). If at least one train stops at the station, the minimum headway must be increased.

2.3.1 Departing headway models

The headway for a train leaving an off-line station should at least meet Eqs. (5) and (6).

\[
I_{f}^{1} = t_u + t_f + \frac{L_{f} + 0.5L_{d,q} + L_{q} + L_s}{\bar{v}_q}
\]
\[
I_{f}^{1} = L_a + L_f + \frac{L_{f} + 0.5L_{d,q} + L_{q} + L_s}{\bar{v}_q}
\]

where \( I_{f}^{1} \) and \( I_{f}^{1} \) are headway and distance interval of the departing train relative to the leading train when the leading train needs to leave at least one energy supply section and the merging switch must be changed to allow the departing train to join the mainline; \( t_f, t_u, L_f \) and \( L_u \) are times of changing and confirming the integrity of the switch and the corresponding distances advanced by the leading train; and \( L_{q} \) is a safety distance. Also, \( L_{q} \) is length of switch; \( L_{q} \) is redundancy distance when a train stops; \( \bar{v}_q \) is the average velocity of the leading train when passing through the switch in its mainline position; and \( L_{f} \) is the distance between the center of the station and the furthest switch in the departure direction. Suppose one station (together with its deceleration and acceleration lanes) corresponds to an energy supply section with length \( L_{s} \), we have:

\[
I_{f}^{1} = \max(0.5L_{s} + L_{q} + 0.5L_{d,q} + L_{u})
\]

After passing through the merging switch, the leading and following trains are on the same route. Thus, train departing headway should also meet Eqs. (1)–(4). Departing headway \( I_{f}^{e} \) is the greater of the headway of Eqs. (2) or (4) and (6). We have:

\[
I_{f}^{e} = \max(I_{f}^{1}, I_{f}^{1})
\]

The calculation method for train departing headway from a station yard is similar to that for intermediate stations. When trains depart from yards of different lengths, safe train headway is assured by considering switch activation time and braking time before the mainline switch. \( I_{f}^{e} \) is then calculated as:

\[
I_{f}^{e} = \max(0.5L_{s} + L_{q} + 0.5L_{d,q} + L_{q} + L_{u})
\]

The result can be put into Eqs. (5) and (6) to obtain the appropriate minimum train departing headway.

2.3.2 Arrival headway models

The headway for a train stopping at an off-line station should meet Eqs. (10) and (11).

\[
I_{s}^{11} = t_u + t_d + \frac{L_{s} + 0.5L_{d,q} + L_{q} + L_{u}}{\bar{v}_h}
\]
where \( L_z^{d1} \) and \( L_z^{f1} \) are the headway and distance interval of the arriving train when the leading train does not stop and the divergent switch position is changed to allow the arriving train onto the deceleration lane into the station; \( t_d, t_v, L_d \) and \( L_v \) are times of changing and confirming the integrity of the divergent switch, and the corresponding distances advanced by the following train; \( \bar{v}_0 \) is the average velocity when the following train passes the switch; \( L_z^j \) is the distance between the furthest switch in the arrival direction and the center of the station. Suppose again that the station lane corresponds to one energy supply section with length \( L_x \), we have:

\[
L_z^d = \max(0.5L_x, L_v + 0.5L_{v,0} + L_b)
\]  

Before changing the divergent switch, the trains are on the same route. Thus, the arrival headway should also meet Eqs. (1) – (4). Train following arrival headway \( (L_z^f) \) is the maximum of the headway of Eqs. ((2) or (4)) and (10). We then have:

\[
L_z^f = \max(I_z, L_z^{d1})
\]  

3. Analysis of Train Following Headway

Train following headway is influenced by many factors such as propulsion system design, train length, speed limit and gradient. We have calculated train following headway for double line operation. All calculations are based on vehicle parameters taken from Transrapid published data(7). As a double-sided energy supplying system can have a shorter headway than the single-sided option, we consider only the double-sided configuration for headway and capacity calculations.

3.1 Analysis of train following headway in sections

In this section, the relationship between the mainline headway of Transrapid trains \( I_z \), velocity \( v \) and the length of energy supplying sections is shown in Fig. 3, as determined by the methodology of this paper, with Transrapid data.

In Fig. 3, the allowable headway \( I_z \) is clearly speed dependent. See for example, curve 2. When \( v \) is within 0 \( \text{km/h} \) – 200 \( \text{km/h} \), \( I_z \) drops quickly. When \( v \) is within 200 \( \text{km/h} \) – 400 \( \text{km/h} \), \( I_z \) drops more slowly. When \( v \) is larger than 400 \( \text{km/h} \), \( I_z \) increases gradually. Thus, there exists an optimal velocity corresponding to the minimum \( I_z \).

3.2 Analysis of train following headway in stations

3.2.1 Departing headway at intermediate stations

From Eqs. (5) – (7), \( L_z^j \) is an important factor that influences the headway for a train departing from an intermediate station. Also, the allowable headway of two trains departing from a station is longer than that of a leading train passing a station and a following train departing from that station. So, the boundary headway is that of two trains departing from a station, as shown in Table 1. The headway of a leading train departing from a station and the following train passing that station will be discussed in 3.2.2.

3.2.2 Arrival headway in intermediate stations

The distance \( L_z^d \) and the speed of a following train \( v \) are main factors that influence the arrival headway at intermediate stations. The headway of a leading train arriving at or passing a station and the following train arriving at that station is mainly influenced by \( L_z^d \). The headway of a leading train arriving at a station and the following train passing that station is mainly influenced by passing velocity \( v \). As the latter headway is usually smaller than the former, it is used as the boundary headway. The relationship of headway and motor section length is shown in Table 2.

3.2.3 Other kinds of headway in stations

The model of train departure headway from identical yards of a sectional station \( (I_z^j) \) is the same as that for departure-departure from an intermediate station. So the trend is similar to Table 1.

The following departure headway from different yards is redefined by the headway of passing a convergent switch. This headway is restricted by the switch changing headway and following headway. The following headway has been discussed previously. The switch changing headway is determined by the passing velocity of a leading train. The velocity is related to yard collocation, the distance between starting place of the leading train and the convergent switch.

The model of arrival headway for a sectional station \( (I_z^j) \) is the same as that for arrival-arrival at an intermediate station. So, the headway is similar to Table 2. The boundary headway in stations is essentially the combination of train departure and arrival movements. Table 3 lists the headway of one such combination, when the leading train departs from a station and the following train arrives at that station.

4. Capacity Analysis of TSMS

Carrying capacity of a Maglev system on a double line is calculated for each direction (up or down). In one direction, carrying capacity is restricted by the minimum of the following: moving carrying capacity \( N_y \), following
departure carrying capacity in station $N_f$, and following arrival carrying capacity in station $N_d$. We have:

$$N_{U(D)} = \min\{N_y, N_f, N_d\}$$

$$C_{U(D)} = \alpha \gamma C_n U_{U(D)} / \beta$$

(14)

(15)

where $N_{U(D)}$ is the maximum section carrying capacity of the up (down) line. $N_y = T / t_x$, $N_f = T / t_f$, $N_d = T / t_d$. $T$ is the operating time per day, $T = 1440 - T_w$ ($T_w$ is maintenance time). $C_{U(D)}$ is the operational passenger load capacity of the up (down) line. $C_n$ is the number of seats in $n$ vehicular sections per train. $\alpha$ is an experiential coefficient which is the ratio between operational capacity and maximum capacity, $\beta$ is a coefficient which is the ratio between operational headway and minimum headway, $\gamma$ is an experiential coefficient which is the average ratio between actual passengers and seats capacity.

Using the above headway models of TSMS, carrying capacity of parallel train schedules can be obtained. The parameters, headway and carrying capacity are shown in Table 4.

We use four scenarios for forecast passenger OD data (shown in Fig. 4), from the China–Japan co-research report completed in 2000(8). Cases 1, 2 are forecast data for 2010. Cases 3, 4 are forecast data for 2020. The difference is that cases 1, 3 only consider flows within the Beijing–Shanghai corridor, while cases 2, 4 include the additional flows passing through Beijing–Shanghai. This data set includes the increased passenger flows generated by the introduction of a Beijing–Shanghai high-speed line. We use this data for comparisons with the carrying capacity of TSMS we obtained for different operating conditions.

In consideration of the increased passenger demands in 2010 and 2020, some possible solutions are illustrated in Fig. 4. The x-axis shows the line sections between Beijing and Shanghai. The y-axis shows the forecast per-direction passenger flows in each section. Five operational possibilities are listed in the figure. For example, “10 – 5 min” means that each Transrapid train has 10 cars and each train operates with a minimum headway of 5 min. Similarly for “4 – 8 min”, “10 – 8 min”, “10 – 10 min” and “6 – 10 min”.

From Fig. 4, the 2010 demand of case 1 for the Beijing–Nanjing section can be met with 6-car trains operating at 10 min headway. If the headway is subsequently
reduced to 8 min, the projected demand for 2020 of case 3 can be met.

The section from Nanjing – Shanghai has the heaviest projected traffic in the Beijing – Shanghai corridor. From Fig. 4, the 2010 demand of case 1 can be served by 10-car trains operating at 8 – 10 min headway. With a subsequent enhanced operation and a headway reduction to 5 – 8 min, the 2010 projected passenger demand of case 2 can be satisfied.

The diurnal peaking in travel demand should also be considered. Suppose the ratio of OD demands at highest peak time (within a 2 hour interval) to total daily flow remains 1:4.5 – 1:6 by previous analysis(9). Considering the Nanjing – Shanghai with highest peak hour traffic, the 2010 demand of case 2 can be served by 10-car trains operating at less than 8 min headway. To meet the 2020 demand of case 3, it appears that headway will need to be reduced to less than 5 min. It seems impossible for Maglev high-speed trains to satisfy much higher capacity demands like case 4 with current technical and financial conditions.

Having determined the headway and consist combinations needed to meet projected passenger demands, this information can now be fed back to determine constraints on section length of the LSM propulsion system by reference to Tables 1 – 3.

5. Conclusions

By analyzing the operational characteristics of the Transrapid Super-speed Maglev System (TSMS), the dynamic train headway models are set up. The headway and line capacity for trains of different consists has been studied with the models. The example of a Beijing – Shanghai Maglev line has been used for capacity analysis. The analysis demonstrates that the headway models and the methods for analyzing the carrying capacity are very useful for operational design of this new ground transportation mode.

References

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