Two Performance Parameters – When *Acceleration* is more important than *Speed* in modern Ground Transportation Systems

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Key Words: Acceleration, Deceleration, Speed

Abstract

Maglev vehicles provide two key advantages over conventional steel wheel/rail type trains: high acceleration and high speed potential. When is one aspect more important than the other, and under what operating conditions? When evaluating the performance of a high-speed ground transportation system, what is paramount is the time taken to transit between stations, which is ultimately reflected in the published timetable. For portions of the system servicing denser urban areas, high acceleration capabilities usually far outweigh the consideration of what top speeds can be reached between stations. In addition, for urban sections of any alignment, what is considered high speed cannot routinely be reached by any system without subjecting passengers to excessive accelerations, due to limits in the ability to accelerate the appreciable mass of the train in a given period of time. The amount of linear acceleration acceptable to passengers, and the curvatures required to tailor an otherwise efficient alignment into the urban area it fitted into, keeps top speed secondary to acceleration.

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1. Introduction

Many are wondering just how useful High Speed Ground Transportation (HSGT) systems will be, and there is a great sense of urgency in the minds of those charged with this aspect of urban planning to put the 'right' type of system forward. Future HSGT systems will compete head to head with the automobile, commuter plane, light rail, and possibly marine ferry systems. The first two of the existing systems just mentioned are capable of relatively high acceleration rates for appreciable time periods, when compared to systems using steel wheel on steel rail for traction. The future system's effectiveness will be evaluated in terms of what the current systems already provide.

In times past in the United States (around 70 years ago), an HSGT type system consisted of a steam locomotive leading a train of around 1.7 million pounds total mass, which was capable of accelerating from a dead stop to around 100 mph in just under 100 seconds. This required a continuous tractive effort of 88,000 lbs, no small feat for a tall wheeled 4-8-4 at 100 mph. Peak acceleration was in the range of 0.045g, but this rate was not possible during low speeds due to adhesion limitations. In addition, it was not possible to maintain for speeds greater than 60 miles an hour due to limits in available horsepower. Two key physical limits worked against this system (not to mention low thermal efficiency); low levels of traction and limitations in the amount of power that could be utilized.

Then, with the automobile by the late sixties people where accelerating to this same speed within 13 seconds, and had covered 0.25 miles getting to this speed, versus 1.4 miles for the steam train. (about $1/5^{th}$ the distance). Acceleration in the case of the automobile was around 0.5g. Taken to an extreme, maintain an acceleration of 1g for 9 seconds and you can cover the same ¼ mile distance with a terminal speed of 198 mph. This calls for good traction (coefficient of friction of 1) between the tires and the road surface.

One reason the automobile and its roadway system became the dominant transportation infrastructure for moving people was not simply the convenience of having one at your disposal; it was the rate of its acceleration and deceleration. If automobiles could not attain acceleration rates appreciably higher than the steam train of long ago, they would not be in wide use even now, and our cities would not be laid out as they are.

In the press to determine which type of HSGT system is most appropriate for a given mission, or purpose, a key system parameter is to what degree and length of time the system accelerate the passengers, within given limitations of accepted passenger comfort and safety. Maglev system acceleration rates are more tied to how much power the system has access to over a section of a route. Without attendant adhesion problems, they can readily absorb high amounts of energy and provide acceleration to match. Steel Wheel/Steel Rail systems can't absorb these levels of power at slow speeds, as slippage will result, with the penalty of high wear. Only when these systems are moving at rates of 60-80 mph can they really consume all the available power that Maglev systems can use almost from the outset.

2. When Is High Acceleration Most Important

In order to provide dimension to this discussion, two candidate systems are reviewed, being capable of two different levels of acceleration.

One is based on a Maglev system whose upper limit of linear acceleration is held to no more than 0.1g [1,3], generally regarded as the limit for passengers who can move about in a train under way, not being restrained.

The other is based on what most consider the reliable limits of adhesion for modern steel wheel/steel rail systems and can attain sustained acceleration of 0.06g [5]. Note that other high power lightweight steel wheel/steel rail systems can't attain more than 0.03g acceleration [4].

Switching from imperial to SI units for the remainder of this paper, the modeled trains have the following common characteristics (the Maglev version and the Steel Wheel/Steel Rail version).

Unique Characteristics of the Maglev Vehicle

- Mass: 600 Metric Tons
- Total Tractive Effort: 600,000 Newtons
- Maximum acceleration rate of vehicle: 0.1 g
- Available total power: 16 megawatts
- Air resistance:0
- Grade: 0%

Unique Characteristics of the Steel Wheel/Steel Rail Train

- Mass: 440 Metric Tons
- Adhesion: 0.24 (easier to achieve at low speeds consistently than at higher speeds)
- Total Tractive effort: 260,000 Newtons
- Maximum acceleration rate of train: 0.06g
- Maximum Power: 8.8 megawatts
- Air Resistance:0
- Grade: 0%

The rationale for neglecting air resistance is twofold. One is that the air resistance force being overcome when accelerating a train to speed is a very small fraction of the total resistance to forward motion, with the majority of the force (in the speed regimes studied here) attributable to that resulting from accelerating the train's mass. The other reason that air resistance isn't included is that it would be fair to say they would be close to equal between the two systems.

Other differences not modeled that have some bearing on the amount of total power each system consumes include that which arises because Maglev is levitated and the HSR system does not consume power to maintain its alignment on the track. At low speeds, under 100 km/h, the Maglev type train may, depending on conditions of the two systems, consume more total power for a given speed than the HSR system. At speeds between 100-120 km/h, the overall electrical efficiency of these two systems will intersect, and from this point on the Maglev system's magnetic drag is less than the rolling resistance drag associated with the HSR train. By the time the two trains reach 300 km/h, the Maglev system consumes about 2/3 the energy to move at a constant speed compared to what the HSR system needs[2].

To summarize the physical characteristics of interest, adhesion constraints limit the acceleration of the HSR train, while passenger comfort and in-vehicle mobility limits Maglev acceleration to 0.1g. For the performance comparisons of the two systems in this paper, the Maglev system has access to 16 Megawatts of power for linear motion and acceleration. The Maglev vehicle has a mass of 600 MT, while the steel wheel steel rail train as a mass of 440 MT, and is of the latest modern type with every other wheel fitted with an electric motor drive for maximum adhesion potential [5]. For this analysis the HSR train has access to 8.8 Megawatts of power for linear motion.

2.1. Basic Physical Differences Reviewed

The following plot illustrates the pertinent data from each train along a 0% grade ROW for a 5-minute time interval.

Allowed to accelerate to the limits of power, adhesion, and passenger comfort levels, the first figure indicates that the Maglev vehicle has about a 1 km lead over the HSR train after about 100 seconds, and about a 2 km lead after just over 175 seconds. At the 5-minute mark, the two systems are separated by 4.3 km. The Maglev's lead, when integrated over many stops and starts over a single day of operation, provides appreciable timesaving as will be shown later.

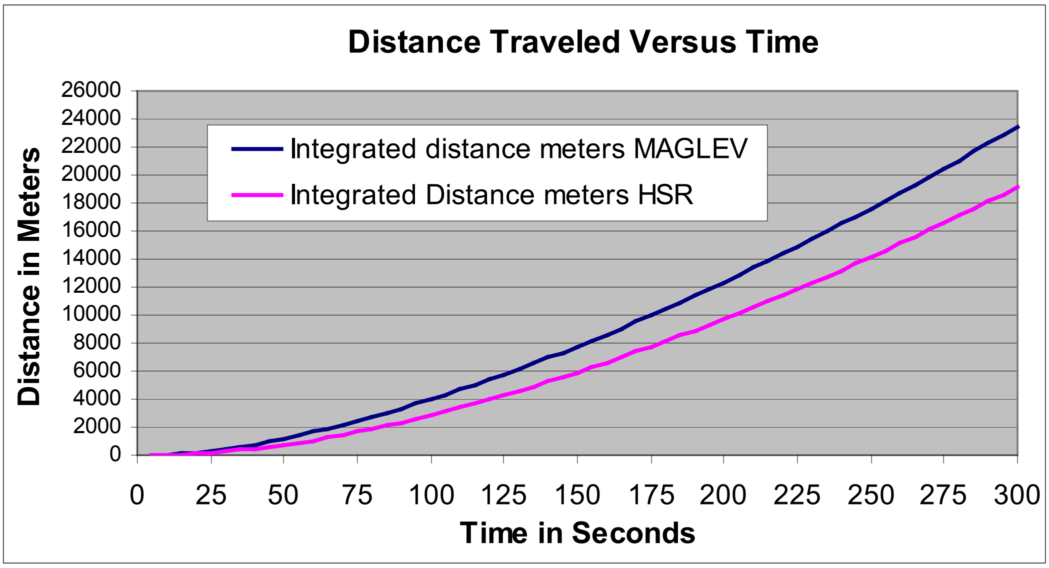

Figure 1

The second figure shows that Maglev acceleration was limited to the rate which passenger comfort dictates for the first 27 seconds, then limited to the available power, 16 megawatts. For the HSR train, adhesion limited the train's acceleration to .06 g until 55 seconds, at which time power limiting occurred (8.8 megawatts available [5]). Once the two systems are power limited (approximately 60 seconds), they exhibit similar acceleration rates since their power to weight ratios are similar, with Maglev having a slightly better ratio. Maglev weighs 600 MT and has 16 MW power, HSR weighs 440 MT and has 8.8 MW power.

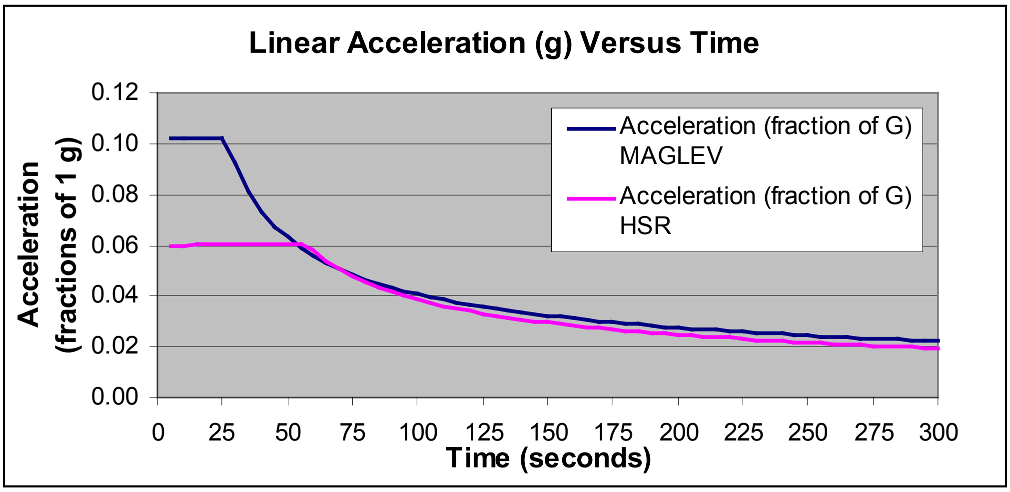

Figure 2

Figure 3 illustrates the speeds reached within the 5-minute interval. Note the change in speed (slope of the line) for the Maglev vehicle almost matches that of the HSR train once power limiting occurs.

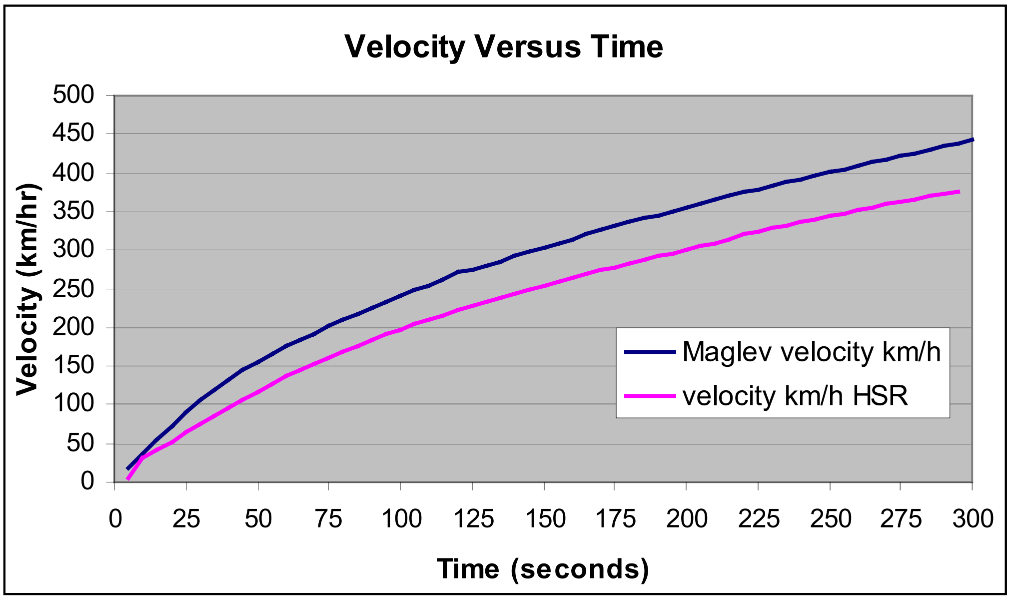

Figure 3

In figure 4, we can see that neither system could absorb full allotted power available at the starting point. In the case of Maglev, drawing this much power would have resulted in accelerating higher than the passenger comfort level. This limiting condition lasted for 27 seconds from the initial start. The HSR train could not draw its allotted power until 60 seconds, as the adhesion constraint limits the amount of current sent to the motors until wheel slip is not likely.

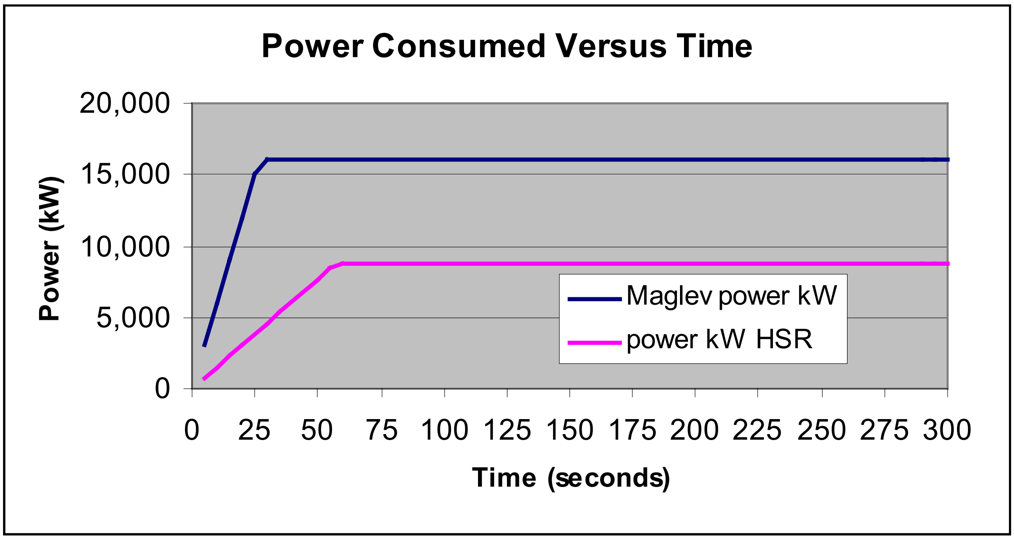

Figure 4

In Figure 5 below, a graph of the tractive effort developed by each system illustrates how the Maglev system allows more available power to be applied to moving the vehicle and its passengers, over the 5-minute interval. This is a crucial advantage. Adhesion limitations cause the HSR train to wait until higher speeds are reached later in the run before all available power can be used for tractive effort [6].

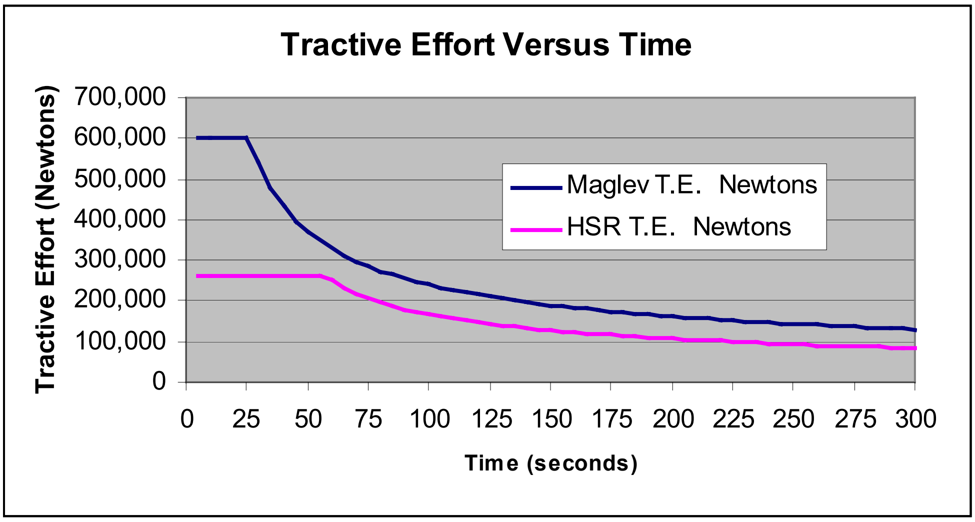

Figure 5

2.2. How Physical Differences Translate to Operational Differences

Revisiting Figure 1, note that the Maglev vehicle led the HSR train by 1 km at 100 seconds. Exploring this difference, a plot of timesavings as a function of the distance between hypothetical stops for the two systems is formulated. For simplicity, the deceleration rates of the two trains are set equal to their acceleration rates. For this initial comparison each system is assumed to use all available power and is otherwise either acceleration limited for comfort (Maglev) or adhesion limited (HSR). Station dwell times at either end point are not included.

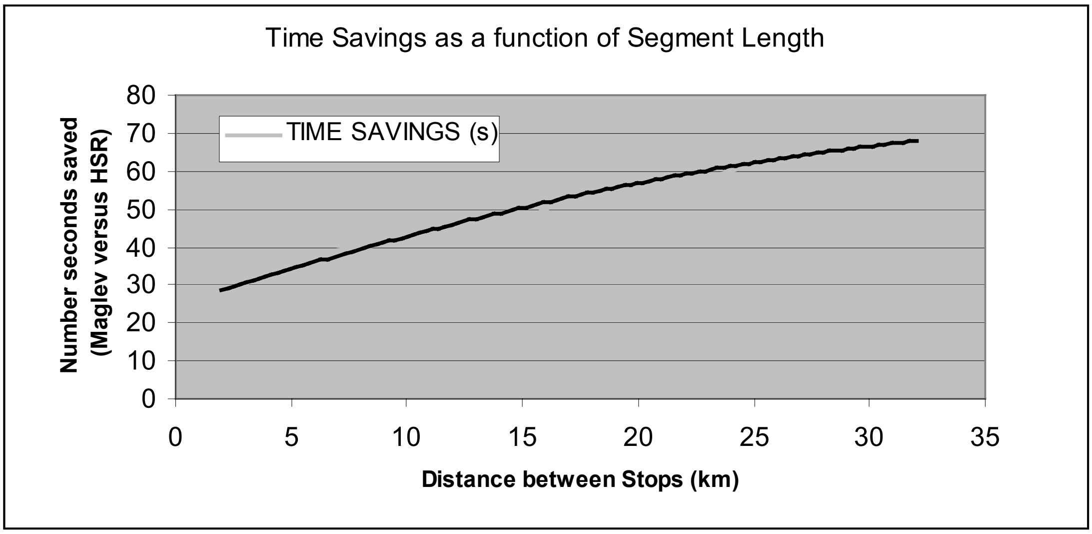

Figure 6

From this data, one can extrapolate the time savings accrued over a typical day where 16 round trips are scheduled.

Five different routes are defined, each with 4 segments with lengths of 6 km, 10 km, 20 km, 30 km, and 40 km. The table below shows the Maglev vehicle timesaving in seconds for one one-way trip along each route, when compared to its HSR counterpart.

Table 1

	Route 1 (km)	time saved (sec)	Route 2 (km)	time saved (sec)	Route 3 (km)	time saved (sec)	Route 4 (km)	time saved (sec)	Route 5 (km)	time saved (sec)
Segment 1	6	38	10	42	20	58	26	64	32	68
Segment 2	6	38	10	42	20	58	26	64	32	68
Segment 3	6	38	10	42	20	58	26	64	32	68
Segment 4	6	38	10	42	20	58	26	64	32	68
Accumulated totals	**24**	**152**	**40**	**168**	**80**	**232**	**104**	**256**	**128**	**272**

Based on this data, if each of the routes were traversed 16 times a day (8 round trips), the accumulated distance covered by both and timesaving for the Maglev vehicle is:

Table 2

Route 1 Timetable	384 km traveled	40.5 minutes saved
Route 2 Timetable	640 km traveled	44.8 minutes saved
Route 3 Timetable	1280 km traveled	61.9 minutes saved
Route 4 Timetable	1664 km traveled	68.3 minutes saved
Route 5 Timetable	2048 km traveled	72.5 minutes saved

3. Is High Speed Ever the Sole Performance Parameter?

The outgrowth of sustained acceleration *is* speed. Based on the performance parameters defined for these systems, for segment lengths greater than 50 km the time savings of Maglev does not appreciably increase beyond what had been accumulated prior to that distance, as the available power was limited to 16 megawatts. Refer to Figure 6 and note that as the distance between stops (x axis), increases the slope of the line that plots the Maglev time savings (y axis) over HSR decreases. Also note that whatever timesaving accrued by Maglev is never lost, regardless of what length of segment is analyzed.

Most people talk in terms of high speed as being very desirable for High Speed Ground Transportation Systems since their own personal experiences are that automobiles that *go fast* also *accelerate fast*. This attribute does not carry over to HSR.

4. Other Advantages of Maglev Over HSR

Maglev lessens the constraints of the alignment planing in the critical urban areas. For example, Maglev can reach speeds of 335 km/h at the 10 km milepost, while HSR can reach 278 km/h, if these two systems are operated to their speed and acceleration limits. If more power is made available to both, these performance parameters will differ even more in short haul to medium haul situations, with the advantage in terms of timesavings going to Maglev. Available power is a primary form of capital investment for the physical plant.

It is logical to design the ROW for higher speeds in the middle third of segments greater than 10-15 km. High speed sections require a greater capital investment in land, construction, temporary traffic diversions, and materials when making long radius curves required for high speed operation. This is true for both systems. For these segments, higher power should be made available at each end portion to accelerate the vehicle (train) up to speed. Maglev is better suited to make good use of these 'ramp up to speed sections', as its speed at the end of a 2 km ramp up, for instance, is 193 km using parameters in this paper, while the HSR system requires approximately 3 km to reach this speed. The middle sections of these segments can get by with less power, even though the speeds are higher, as the power required for acceleration is less in these areas.

5. Conclusions

Maglev vehicles offer the urban transportation planner a system that saves people time, when compared to other forms of high-speed ground transportation systems. If a 80 km route made from four 20 km segments is traversed at full acceleration potential 16 times over an operational day, neglecting station dwell times, a 61.9 minute savings is realized when compared to a system constrained to adhesion limits of the most modern, highest adhesion HSR system. This is a very significant amount of time in any timetable, and can be used for more station dwell time for passenger loading and unloading, or reduce the number of running vehicles. In order to realize this level of performance potential, the amount of power the system is budgeted to consume is very important. It takes power to move people, and the system that can absorb it most efficiently will always provide the transportation planner the most flexible and highest performing alternative.

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