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Boltzmann's Analysis of Commuter Train Transport to "Hot Spot" Tokyo

by

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Abstract

Transport by rail is becoming more and more important as one means resolving the global warming. The goal of this paper is to analyze social hot spots, which are areas of high energy or activity in general and find simple criteria for judging the efficiency of commuter train systems as shown by the very efficient commuter train system in Tokyo as an example. Train capacity as a function of the inhabitants of a suburb city, where commuters come from, is one measure for the efficiency of the train system. Another one is the travel speed against travel distance. The results of tis analysis show that areas with high-speed commuter trains are also the mostly populated areas. The results of analysing social hot spots can be applied to similar hot spot problems in material science, where electrons or phonons are gathered.

Keywords: Transport simulation, Particle flow, Material science, Boltzmann analysis, Tokyo

1. Introduction

Transport by rail is one of the most efficient and energy conserving transport systems on ground. The serious problem of global warming requires a strong demand to increase transport by rail, because electric trains are more environmentally benign than automobiles. The commuter train network in greater Tokyo area is the densest and most frequent running train system in the world and is a kind of model for public urban transport in other cities. On the other hand transport on rail has to compete against the convenient self-driven car transport, which is often faster when concerning the time form door to door. Also a serious problem for future will be the passengers fear against bacteria when traveling in densely packed commuter trains.

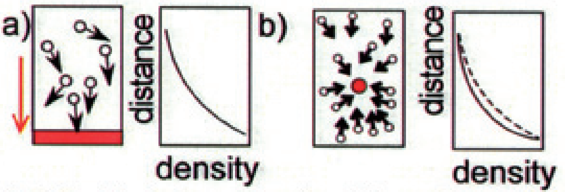

Fig. 1 Particles density as a function of distance for (a) planar geometry as described by barometric formula, (b) two-dimensional geometry.

The goal of this paper is to find simple criteria for judging the efficiency of commuter train systems. As shown below this has a great impact also for related problems in material science, especially solid state physics. Using suitable mathematical models, different commuter railway lines can be compared. Achievements and challenges become obvious and transport planning becomes easier. The tasks for any transport system are, (a) it should be sustainable, (b) use as minimum resources as possible, (c) should be an optimization between customers wishes and costs, and (d) convenient and acceptable for costumers. Inside transport companies there are presumably already methods developed for best transport solutions on a certain line, but analysis of the whole transportation network is often missing.

Modeling of traffic has become a popular subject since computers were available. In order to deal with the large amount of data, they are best

Fig. 2 Commuter traffic in Tokyo is the densest public transport system in the world.

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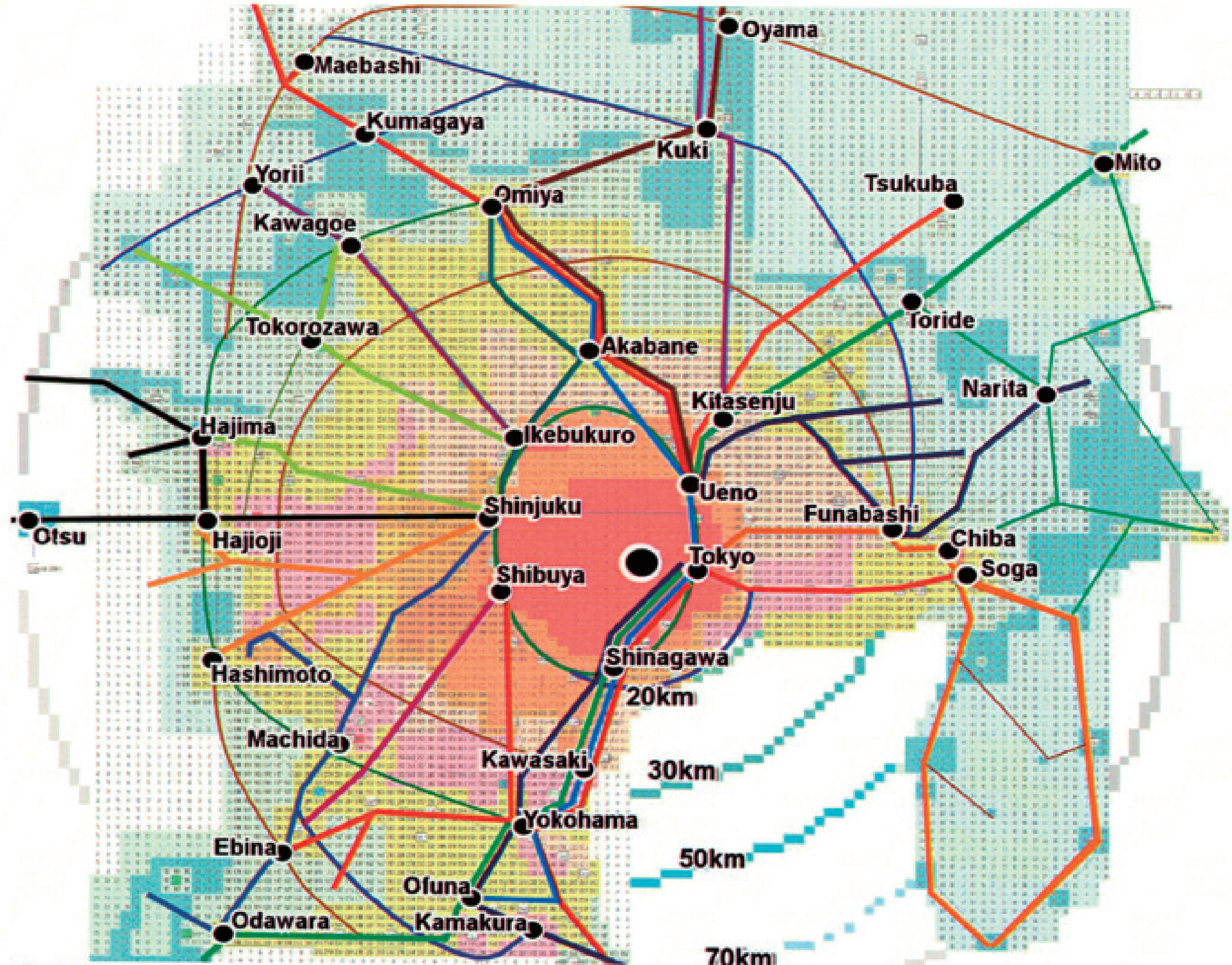

Fig. 3. Map of railway lines and major transfer stations in greater Tokyo area. The colored regions show the real estate price (red = very high, orange, pink = high, yellow = middle, light green, blue = low). The map is drawn in centered logarithmic scale in order to emphasize the commuter lines compared to ring lines.

handled with numerical simulations, which are usually applied in order to understand car congestion on freeways1,2), pedestrian congestions at escalators or train doors 1, 3), or for disposition of wagons or train unit runs. Scientists found out that objects in traffic behave like moving gas particles in Boltzmann's kinetic gas theory and the following corresponding principles between physics and traffic were found

Particle – car, train or pedestrian
Energy – activeness of pedestrians
Temperature – progess of passenger flow
Force – attraction or motivation to go somewhere.

Velocity, time, space, density are the same for both, traffic units or gas particles. The success of such approach was that the reason for congestion on freeways could be understood much better and that escalators were placed sufficiently and at the correct place. Another such parameter is the price for real-estate 4), as it is proportional to population density.

Another phenomenon is discussed in both, physics as well as traffic simulation: Hot spots are in general areas of high energy or activity. In social life this means a place where many people gather together. In this sense the commuter traffic is the best example for the "hot spot" Tokyo (fig.2, 3)5, 6).

Also in physics hot spots have been defined in several independent areas as the following five examples show. (A) They can be centers of high electric current, which even can lead to the break-down of semiconductor devices 7). In solar cells 8) or thermoelectric devices9) with nano-structure such hot spots can lead to serious damage or at least reduction of the performance. (B) In a similar sense, hot spots at nano-particles are places of enhanced optical activity, either due to absorption or emission of light. Such activity has been theoretically predicted10) and by methods such as surface-enhanced Raman scattering the detection of single molecule is possible11). (C) Nonlinearities in metal solidification, in particular in the temperature profile of combustion engines cause hot spot problems in engineering. (D) In deformed metals dislocation avalanches can create thermal host spots12), which can transform meta-stable crystals13). (E) In nuclear engineering hot spots are particles within the fuel with high radioactive emission14). The later two phenomena are caused by inhomogeneous distribution of material, but the others are caused by particle gathering due to attractive forces or self-stimulating cycles, which can be for example for semiconductor devices a higher electron density means higher temperature. Due to polarization this changes the local electric field and creates more electrons and so forth.

Fig. 4. Cities in greater Tokyo area are shown together with commuter lines. The large circles mark distances of 15, 30 and 45 km to Tokyo center (Kasumigaseki).

In the case of Tokyo the self-stimulating cycle can be explained easily. After Tokyo became the capital of Japan, more and more companies moved their headquarters to Tokyo and more and more employees moved here. Large department chains established stores and this attracted more costumers. Hence, it became an attractive, sustainable city, even for cultural life. In solid-state physics such self-stimulation cycles are hardly understood. Even the flow of electrons, phonons, polarons, charge density waves, or other particles is not yet completely understood. Hence, another goal of this paper is to check which mathematical model can be applied for such situation.

Fig. 1 shows the movement of particles under forces. In the one-dimensional case (a) of barometric formula gas particles are driven by gravity forces. Due to mutual collision as described by Boltzmann kinetic gas theory the density decreases as function of the distance from the Earth surface. In the two-dimensional flow of particles (2) as in the considered example of the hot spot Tokyo (fig. 2) the density profile is expected to decrease faster, and in three-dimensions the material science particles density decrease presumably even more rapidly.

This paper is organized as following; first the calculation methods are described, than the data are summarized and discussed.

2. Calculation Method

A map of real estate prices[4] (fig.3) was drawn with Excel software. Major railway lines and their connecting stations were transferred from a linear scaled map to this centro-logarithmic map with extended radial scale in the middle and shrunken scale at the outside. Then the data of real estate price[4] were inserted in each field and neighboring fields were interpolated unless the data are known. Then the map was colored showing equal colors for equal prices.

The map of the distance dependence of commuter lines (fig. 4) was adapted from MS AutoRoute Software. Each point marks a city, village or wards of the five major cities Tokyo, Yokohama, Kawasaki, Saitama or Chiba, abbreviated as T, Y, K, S, or C in the following. Circles marking the 15, 30, 45 km distance from the center of Tokyo, Kasumigaseki, were drawn and then the railway lines were copied on this map.

According to this map, cities which lie in the distance between 36 and 45km were considered as starting points for commuter trains analyzed in the following. Over this distance rail transport is best and most efficient, compared to other transport systems is. Hence, interference from other is less, as car travel for such long distance is too slow, motor bike or bus travel too far. For the proof of a mathematical model it is necessary to assume that there is no such disturbance. The topography of Tokyo is not perfect, as the Tokyo bay creates a hole in the otherwise star-shaped pattern of train lines, but this is partly compensated, because of high population densities at the costal areas of Tokyo Bay.

Table 1 Data of cities, their railway lines with travel time, distance, train capacity used in this study.

Cities	Line	Inhabitants	travel time [min]	Travel Distance [km]	Train frequency f [1/h]	Number of Coaches n	Capacity C=f*n
Ebina	Odakyu	621504	68	46.3	17	10	170
Ebina	Sotetsu		84	54.2	13	10	130
Yamato	Denentoshi	605671	62	36.8	13	10	130
Y, Izumiku	Sotetsu	155178	74	49.2	14	8	112
Fujisawa	Tokaido	888976	67	45.9	16	15	240
Kamakura	Yokosuka	595881	84	48.8	9	15	135
Y, Totsuka-ku	Tokaido	820351	48	41.5	16	15	240
Y, Totsuka-ku	JR-Shinjuku		53	48.6	5	15	75
Y, Konan-ku	Negishi	545939	66	53.2	13	11	143
Y, Konan-ku	JR-Shinjuku		66	52.5	5	15	75
Y, Kanazawa-ku	Keikyuu	439009	76	47.7	27	10	270
Futtsu	Uchibo/Keikyo	50178	124	100.5	2	6	12
Kisarazu	Uchibo/Keikyo	517645	107	75.2	15	6	90
Sakura	Sobu	575064	78	58.3	10	10	100
Inba	Hokuse	61766	74	44.3	9	10	90
Toride	Joban	806521	56	44.7	15	10	150
Tsukuba	TX	260753	57	42.7	17	6	102
Noda	TX	154677	65	41.3	8	6	48
Satte	Tobu-Nikko	54631	80	52.2	8	6	48
Kuki	Tohoku	73349	75	51.3	5	15	75
Kitamoto	Takasaki	70107	69	49.1	9	15	135
Kumagaya	Takasaki	334022	87	67.1	3	15	45
Sakado	Tobu-Tojo	100145	77	51.4	13	10	130
Kawagoe	Tobu-Tojo	333377	85	49.0	13	10	130
Hidaka	Saikyou	55402	80	55.8	4	10	40
Hanno	Seibu	84214	70	54.5	8	10	80
Hamura	Chuo	199258	73	45.5	11	10	110
Akiruno	Seibu	81475	84	44.2	5	10	50
Hajioji, JR	Chuo	570967	73	43.2	16	10	160
Hajioji, Keio	Keio	570967	78	43.7	7	10	70
Sagamihara	Odakyu	707976	73	42.5	22	10	220

For fig. 5 the number of inhabitants for each city was taken from internet data[3]. It was often found, that in a city lay several railway stations. When these stations belong to the same line, there is no problem in counting these data. When they belong to different lines, the number of inhabitants was split into portions according to the length of the cross section through the city. Several cities have no train connection; these were counted for stations in the neighborhood.

The travel time from the listed cities to Tokyo center (Kasumigaseki) was checked in the timetable for each railway line. The morning rush-hour was considered, namely the train should arrive at the destination Kasumigaseki before 9:00h a.m. In many cases transfers were necessary, and the transfer time was included. The train, in which passengers travel the longest portion on their journey to the destination, was used in order to calculated the capacity C as $C = n * f$, where n is the number of wagons per train and f the frequency of trains per hour. The number of wagons per train was counted by inspection of each train. In the case that there are slow and fast trains, only the fast express trains without extra payment were used for this analysis, because the slow trains were considered to have other functions, as collectors of local destination passengers. Indeed their capacity is much less and travel time much longer. Many of the commuter lines towards Tokyo have separated tracks for express and slow trains. This is already automatically included in an indirect manner, as the travel time is faster on these lines.

3. Results and Discussion

The map of the major railway stations in Tokyo area fig. 3 shows that the railway network has formed a kind of spider net with tow types of lines, central lines to the center and ring lines as connecting lines in between. The Yamanote line is a ring line with a radius of about 7 km, the at 20 km follows the Rinkai line, that at 30 km, the Nanbu-, and Musashino- lines, at 40-50 km the Yokohama-, Kawagoe- and Shinkeisei- lines and finally a larger circle following the Sagami-, Chichibu-, Tobu-Isesaki-, Tobu-Noda, Kanto- and Narita-lines. The colors refer to the prices for real estate and shows in red very high prices at the southern part of Yamanote-circle, then in dark orange areas of the northen part and the area between Tokyo and Yokohama, then in pink regions between Yokohama and Machida towards the Chuo-line and between Tokyo and Funabashi, followed by regions in yellow as farer commuter areas and the popular Kamakura area, while light green and light blue areas are almost rural areas. This analysis indeed shows that real estate prices near fast railway lines are more expensive, especially at Tokaido-, Chuo-, Tobu-, Saikyo-, and Jouban-lines. In other word, railway lines have a great influence on urban development.

The data in table 1 were used for the following plots. The train capacity versus the number of inhabitants for different cities in a distance of 35 between 45 km is shown in fig. 5. The train capacity was calculated as frequency multiplied by train coaches. The line in the graph is a guide line to show the average. As each train coach can carry more than 90 passengers

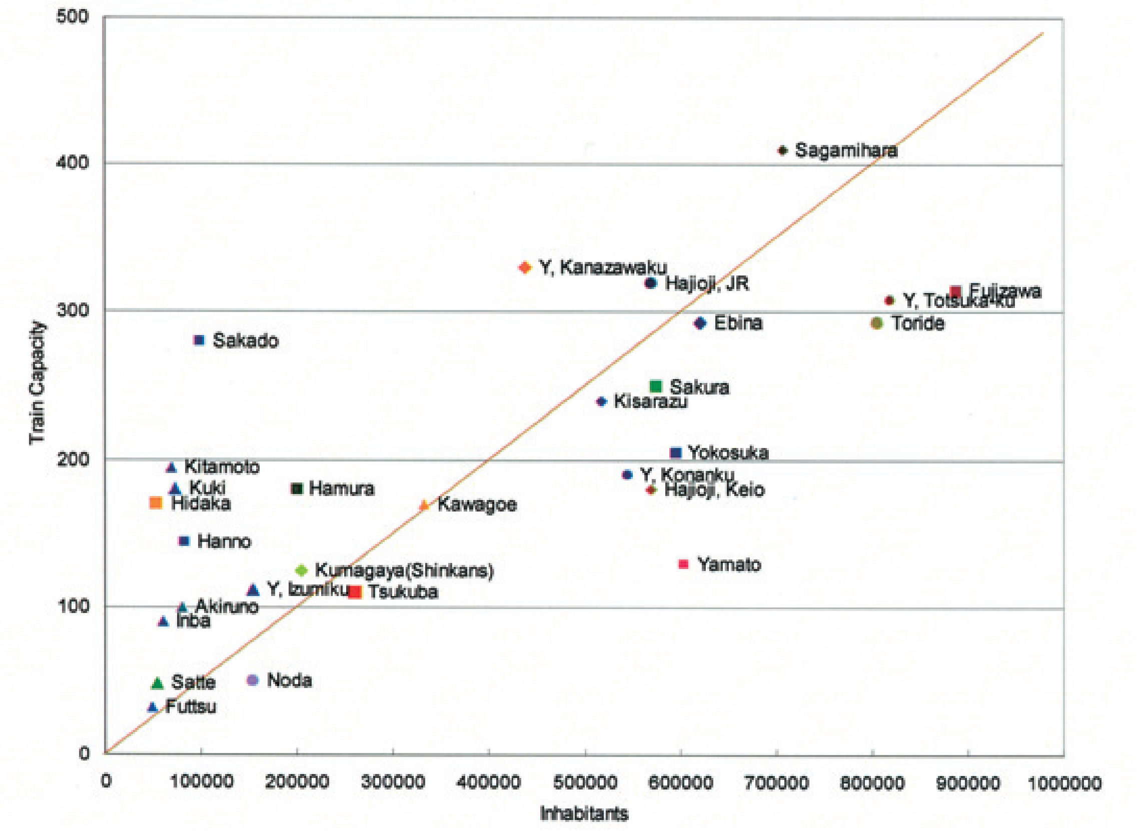

Fig. 5. Commuter train capacity as a function of inhabitants of cities a distance of 36 to 45 km from Tokyo.

including the standing passengers, the line shows that in average about 5% of inhabitants commute daily to work. Cities below the line have a lack of commuter train capacity. This is conform with own experience. The Denentoshi line starting from Yamato is known for its crowding during rush hours. Cities on the left side of the average line have sufficient train capacity. In many cases of distant cities with less population, like Kuki, Satado or others, the train companies run long trains with overcapacity through to these cities, because a return in stations before would cause more inefficient costs In the case of Kitamoto long trains are cominng from Maebashi and are already quite packed when arriving at this station.

Fig.6 shows the travel time as a function of the travel distance. As mentioned above all considered cities are lying in a direct distance of 35 between 45 km. If the travel distance is much longer, it means that the railway line makes a long way around to reach the goal. In the case of Futtsu and Kisarazu the Tokyo Bay is an obstable and almost doubles the real distance. In fig.6, the average line is again a kind of guideline, which railway lines work effective, and which not. The data points of railway lines which lie below the average, have a faster travel time than average. These lines are mainly the JR main lines, like Jouban, Yokosuka, Tokaido, Utsunomiya lines, and the newly build, private Tsukuba Express. The Shinkansen connection to Kumamoto is an exception and costs additional surcharge. The slowest travel times are achieved for connection with a lot of changing trains. Cities with such connection are of course not so popular at least for commuting people. If checked on the real estate price map (fig.5) indeed the price for these cities is lower compared to other cities in the same distance.

These two simple analyses show the power of numerical data analysis. Train capacity and travel time are the two most important criteria, which passengers make to choose a certain transportation system; others are travel fee, seat capacity, access, reliability, or others. The data shown here were based on the inhabitants of each city, which is a quite rough data acquisition, better is to use only inhabitants live near the railway stations.

The next step is to evaluate the distance dependence, which is necessary to compare to the physical models as mentioned in the introduction. The railway network pattern has very much similarity to Lichtenberg pattern and it will be a challenge to detect other similarities, in particular whether correlated electrons are bundled as trains are bundling many passengers.

4. Conclusion

The rail network in Kanto area is one of the most efficient and energy conserving transport systems in the world.

(1) Analysis of train lines showed, that the rail network can be divided roughly in two types of lines, direct commuter lines and ring lines, which support the commuter lines. Most of the commuter lines are directly connected to the subway lines with through-running trains. There are 25 commuter lines running towards Tokyo, which means that at an average

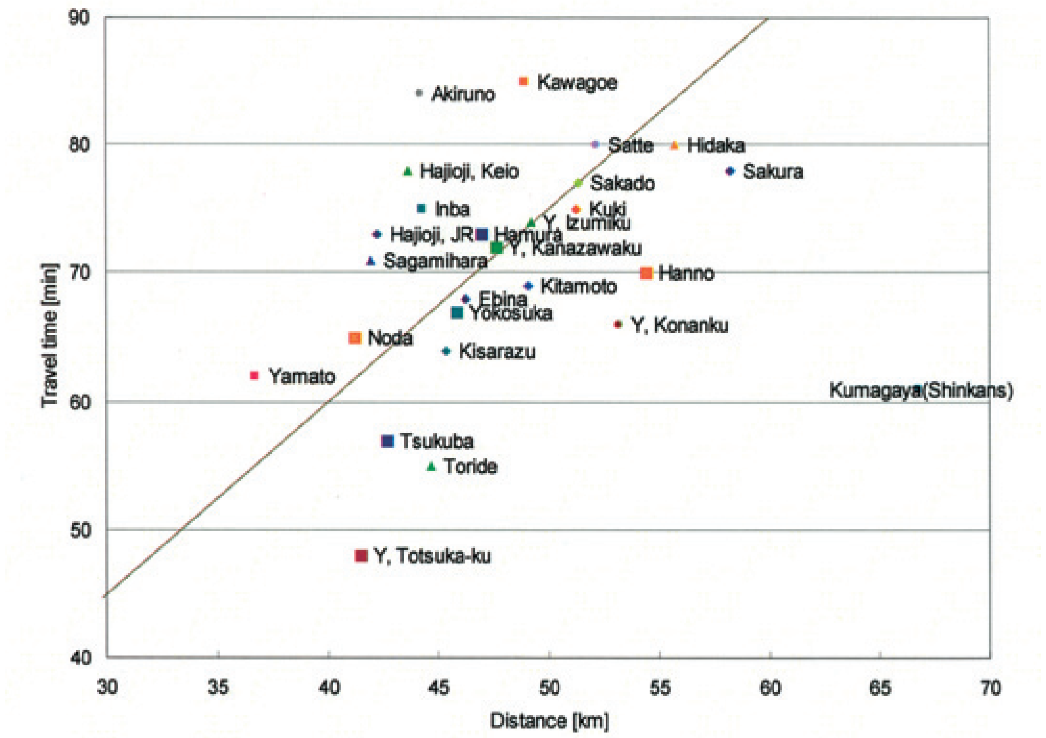

Fig. 6. Travel time of commuter train as a function of distance for cities in a direct distance between 36 and 45 km.

angle of every 365/25= 14.6 degree a line with a distance to the center of at least 40 km, in a distance of 20km there are four more lines, so the angle decreases to 12°. Real estate prices near railway line are higher than in other areas.

(2) From the plot inhabitants versus train capacity densely packed trains can be distinguished from less denser trains.

(3) The plot travel time as the most important criterion for passengers. It judges the efficiency of train transport.

(4) The criteria can be used to evaluate physical models for hot spots in solid state physics.

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