DEVELOPMENT OF MAGLEV URBAN TRANSPORTATION SYSTEM AND ITS APPLICATIONS

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1. BACKGROUND AND HISTORY OF RESEARCH AND DEVELOPMENT

1.1. New Urban Transportation System in Japan

In order to solve several problems concerning urban transportation such as traffic nuisance, accident and congestion, mono rails, rubber-tired new transportation systems (People Mover, AGT) and linear motor subways have been developed and put to practical use. As shown in Table 1, these systems have been used in commercial operation as urban transportation systems in Japan.

1.2. Effectiveness of Magnetic-levitated Urban Transportation System

As stated in the preceding section, those new urban transportation systems have been effective. However, if we adopt the non-adhesive drive by linear motor for propulsion and the magnetic levitation for support of a vehicle, lower-nuisance and -cost urban transportation systems could be realized.

Since the magnetic-levitated transportation system makes it possible for vehicles to move at a high speed, transportation systems for high speed or ultra-high speed running such as superconductivity MAGLEV of the Japanese JR group or the German Transrapid have been developed. The transportation system, however, has many advantages as an urban transportation system running at a relatively low speed. That is, since there is no direct mechanical contact between a vehicle and a track, the following advantages can be expected.

(1) Noise and vibration are small, nuisance low and riding quality good.
(2) Since adhesion is not necessary, vehicles can run on steep grades, an the transportation system is not influenced by climate and rail conditions.
(3) Since no parts are abraded, maintenance cost for track, vehicles, etc. can be reduced.

In addition, vehicles do not use wheels, and are supported on the track by magnets, and it makes the following points possible.

(1) Support for a vehicle will be close to be uniform distributed load in the direction of a vehicle longitude, and there is the possibility that

Table 1 New Urban Transportation Systems in Japan

	New transportation systems			
Line	Port Island Line	Port Town Line	Kanazawa Seaside Line	Rinkai Line
City	Kobe	Ohsaka	Yokohama	Tokyo
Route length(km)	6.4	6.6	10.6	12
The number of stations	9	8	14	12
Construction expenses per kilometer(million yen)	6830	6090	5960	8540
Begining of service (expected)	1981	1981	1989	(1994)
Type	Side guided	Side guided	Side guided	Side guided
Passenger capacity(persons per car)	73 or 75	72 or 75	66 or 75	54 or 63
No. of cars in a train set	6	4	5	6
Schedule speed (km/h)	21	27	26	30
The number of passengers carried per day (1987)	43,260	55,250	85,000 (estimated)	100,000 (estimated)
Operation	Full automatic, without operator	Automatic, with operator	Manual, by operator	Full automatic, without operator
Electric source	AC3φ600V	AC3φ600V	DC 750V	AC3φ600V
	Monorails		Linear Metros	
Line	Kokura Line	Yamanote Line	Ohsaka The 7th Line	Tokyo The 12th Line
City	Kita-Kyuushuu	Chiba	Ohsaka	Tokyo
Route length(km)	8.4	11.8	5.2	3.8
The number of stations	12	13	5	4
Construction expenses per kilometer(million yen)	8000	9600	19,700	20,000
Begining of service	1985	1988	1990	1991
Type	Straddled	Suspended	Linear motor driven	Linear motor driven
Passenger capacity(persons per car)	114 or 125	79 or 88	90 or 100	90 or 100
No. of cars in a train set	4	2	4	6
Schedule speed (km/h)	27	28	35	33.0 ~ 35.5
The number of passengers carried per day (1987)	26,280	11,500	80,000 (estimated)	44,000 (estimated)
Operation	Automatic, with operator	Manual, by operator	Manual, by operator	Automatic, with operator
Electric source	DC 1500V	DC 1500V	DC 1500V	DC 1500V

lightweight of vehicles and simplification of track work can reduce construction costs.

(2) Since no mechanical contact is necessary to generate turning force of vehicles, trucks can be structured so that they can pass through sharp curves. (An existing system is designed so that vehicles can pass through curves of which radius is 25mR.

1.3. Research Project for Practical Use

The authors have been engaged in research on a linear motor subway system in which vehicles supported by steel wheels are driven by linear induction motors, and succeeded in its practical use. (The linear motor subway was put to commercial operation in Osaka in 1990.) Now, we have conducted tests to further make use of advantages of non-contact drive by a linear motor, and to put a magnetic levitation system which supports vehicles with magnetism to practical use as a urban transportation system.

A system which the authors have researched on and developed is electromagnetic-levitated by electromagnets, and uses a linear induction motor. Compared with systems which use superconductivity magnets or linear synchronous motors, the levitation system poses fewer problems, and is expected to be put to practical use in the near future.

The electromagnetic levitation system has had results of practical use as an in-park transportation system at exhibitions, but has no record of being used as an urban transportation system except few small systems. In addition, since the levitation system is extremely different from ordinary railways, it is necessary to verify its safety, reliability and economic efficiency, including failure and trouble occurrence, in order to put it to practical use.

Therefore, a prototype of vehicles and a track have been constructed for tests, and a project for research and development has been implemented to conduct running tests and to verity practicability since 1989. This project has been considered by the Feasibility Study Committee for Urban Mass Transit by Linear Motor Driven MAGLEV (Committee chairman: Eisuke MASADA, professor of the University of Tokyo). And Chuubu HSST Development Corp. was established as joint venture of Aichi Prefecture, Nagoya Railroad Company, and HSST Corp. etc. in order to conduct the running test. They started manufacturing test trains and constructing a testing line, and completed them in April, 1991.

The Ministry of Transport has also examined and considered the linear motor system in the study committee on technical evaluation for the EMS (Electro Magnetic System) type MAGLEV transportation systems, and the ministry's Traffic Safety & Nuisance Research Institute will conduct evaluation tests to assess its safety, reliability, etc. to put this type of a system to practical use in cooperation with Chuubu HSST Development Corp.

In the following section, the outlines of the testing line constructed in Nagoya City, the HSST-100 system, and evaluation tests implemented on the testing line will be explained.

2. HSST-100 SYSTEM AND ITS DEVELOPMENT HISTORY

Characteristics of the HSST-100 system developed for urban transportation and its development history are briefly explained.

The HSST is a EMS type MAGLEV transportation system which Japan Air Lines started developing in 1974. In this system, of which details will be explained in the following section, electromagnets mounted on a lower section of the vehicle attract inverted U-shaped rails mounted on a girder from the bottom to support the vehicle. Clearance between rails and the electromagnets is always monitored by sensors, and the clearance is maintained to be constant by control the amount of current passing through the electromagnets. The vehicle is driven and braked in non-contact by linear induction motors, of which primary coils are attached on the vehicle and secondary conductors called reaction plates are distributed on a track. A section corresponding to a truck consisting of electromagnets, linear motor coils, etc. is called a module.

So far, five types of systems, the HSST-01 to -05, have been manufactured. The HSST-01 and -02 systems were for tests, and the HSST-03 to -05 systems were of practical size which were assumed to be used for passenger transportation. A controller was placed on the ground for the HSST-03 system (operated in the expositions held in Tsukuba and Vancouver), and the HSST-04 system (exhibited in the Saitama Expo) and the HSST-05 system (exhibited in the Yokohama Expo) were practical types with the controller on board.

While the HSST-04 and -05 systems were vehicles for inter-city transportation systems with a velocity of about 200 km/h, the HSST-100 system developed lately is for an urban transportation system with a velocity of about 100 km/h. Therefore, the overall vehicle length is 8.5m, similar to that of a rubber-tired people mover system, and the vehicle has a standing section.

Since a vehicle length of the HSST-100 system is short, a module per vehicle is six units with three on one side, fewer than eight for the HSST-04 and -05 systems. The levitation clearance produced by electromagnets is 8mm, reduced by 1mm from 9mm of the HSST-04 and -05 by making use of the past experience.

Table-2 shows the outlines of the HSST-100 system.

3. OUTLINES OF TEST VEHICLE AND LINE

3.1. Test Vehicle

3.1.1. Outlines

A test train, made of aluminum alloy, is made up of two coaches (commercial train made up of four coaches), and its weight is reduced by making use of advantages of uniform-load support. (In order to save power for levitation, the weight is targetted at less than one ton per 1m of a module on one side under full load.) The vehicle has six modules per coach (the module corresponding to a truck of a railway train, and the modules on one side counted by one). The module is made up of four pieces of magnets for levitation and guidance, one piece of a primary coil for a linear motor, a hydraulic brake, etc.

The VVVF inverter for motor control, a magnet driver for levitation magnets, and other are mounted on the vehicle, and the electric power for these equipment is collected from DC 1500V trolley line on the side of the girder.

Fig. 1 shows a schematic picture of the vehicle.

Table 2 Specification of HSST-100 System

VEHICLE	Number of cars	2
	Passenger capacity	About 90 persons per car
	Dimensions	Length:8.5m,Width:2.6m,Height:3.3m
	Weight	Empty : 21.3t/2cars Full loaded : 30 t/2cars
	Air gap	8 mm
	Propulsion	Six short stator LIMs on each car
	Maximum speed	110 km/h
	Acceleration	Max. 4.5 km/h/s
	Deceleration	Max. 4.5 km/h/s (Service brake) Max. 5.3 km/h/s (Emergency)
TRACK	Distance between the railes	1700mm
	Minimum curve radius Vertical curve radius	100m (25m in turnout line) Min. 700m
	Cant	Max. 8°
	Maximum gradient	7%
	Route length	Approximately 1.5km
ELECTRIC POWER	Supply	DC-1500V

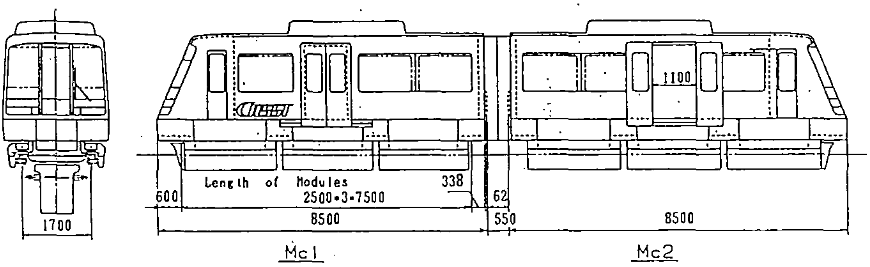

Fig.1 Test Train

3.1.2. Levitation/Guidance System and Suspension System

The vehicle is supported and guided by attractive force working between electromagnets and rails. That is, a core of a U-shaped electromagnet which is faced with a an inverted U-shaped rail consists of an electromagnetic circuit. Vertical gap is controlled to be constant for levitation, and the guidance uses restoring force due lateral displacement. A cross section of the module is shown in Fig. 2.

(1) Levitation Control

Each module has two pairs of levitation/guidance electromagnets (pair magnet), and a control system consists of gap sensors, which are mounted at the front and back of each module, an acceleration sensor, a levitation controller and a magnet driver . A schematic picture of the control system is shown in Fig. 3. Each pair magnet is basically controlled independently.

Its control system is a feed-back type in which electromagnetic current is controlled in response to displacement input from the gap sensor and acceleration input from the solution sensor so that the levitation gap becomes a constant value (8mm for the HSST-100 system).

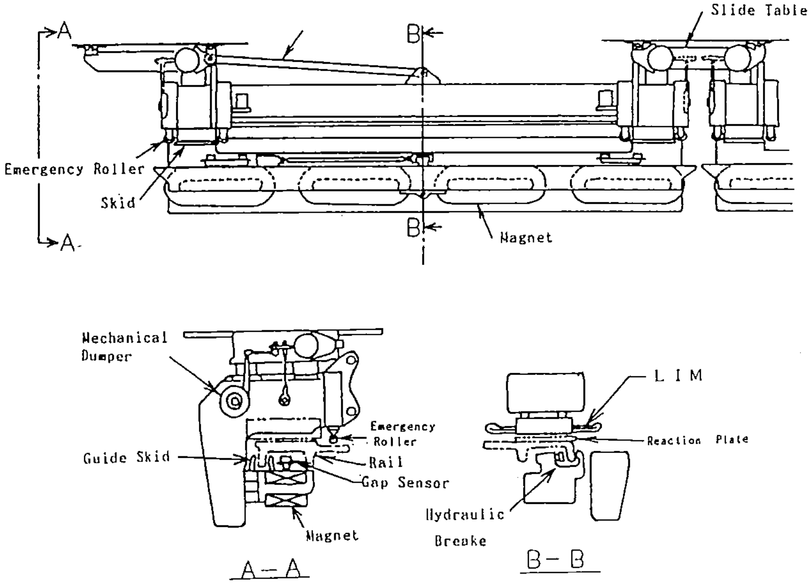

Fig.2 Structure of Module

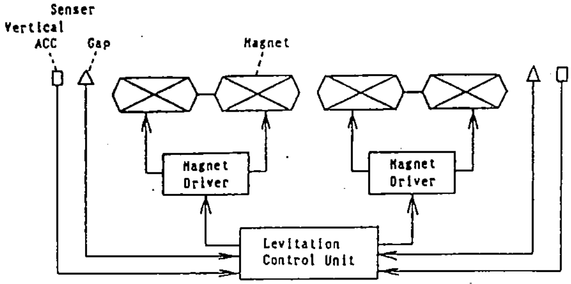

Fig.3 Diagram of Levitation Control System

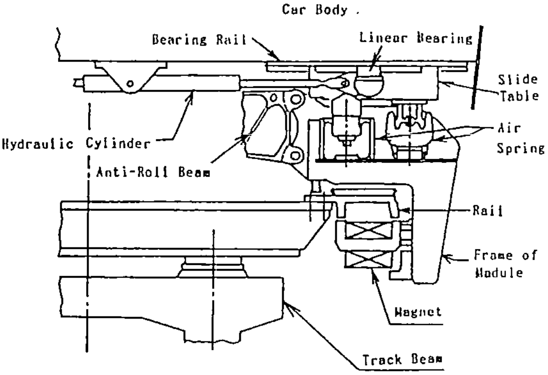

Fig.4 Vehicle Suspension System

(2) Guidance Control

Since this system adopts a method to control the current of the electromagnets and lateral position cannot be directly controlled, the restoring force due to lateral displacement is used. When rails and electromagnet cores are displaced, it causes reduction in the levitation force and the increase a clearance between the rails and the electromagnet. To restore the clearance, the electromagnetic current is increased. As a result, guidance force is generated, and the electromagnets move in the direction to dissolve the lateral displacement.

(3) Suspension System

A basic structure of the suspension system consists of the module unit, a sliding table and a vehicle body.

As for vertical support, sliding tables are placed on both ends of the top of the module, and the vehicle is designed to be mounted on the sliding tables. Between the module and sliding tables, two units of air springs are placed in parallel (Fig. 4).

Three units of the modules on one side are connected with each other through sliding tables located between them while permitting their free movement in the yaw direction, but they have a kind of a hydraulic steering mechanism. That is, sliding tables on both ends and in the middle are linked through a hydraulic system, and the middle sliding table is displaced by as much as half of the amount of horizontal displacement of the end sliding table (Fig. 5). This makes it easy for a vehicle to pass through sharp curves.

(4) Measures against Troubles

As far as troubles of the levitation system is concerned, when one module is in trouble, the troubled module alone are grounded by using a skid, and the vehicle is propelled by thrust of linear motors. When two or more modules are in trouble, the vehicle is supported by emergency rollers after being grounded using skids, and the vehicle is propelled by thrust of linear motors. These troubles are detected with watching both gap and over current of electromagnets.

Since this system generates guidance force in accordance with levitation movement, the guidance force is not generated when trouble takes place. Therefore, the guidance force is obtained through guiding skids in case of trouble.

3.1.3 Propulsion and Braking Systems

A propulsion method is a on-board primary linear induction motor (LIM) with a primary coil being mounted in a module of the vehicle. Thrust force is obtained from the interaction of induction field by shifting magnetic field generated in the primary coil and eddy current generated in the secondary conductor (reaction plate). Electric brake of a linear motor is mainly used under normal condition.

(1) LIM

One unit of LIM is mounted on each module with its rating 55kW, the maximum output when used. Twelve motors on two vehicles can generate about 40kN, the maximum thrust.

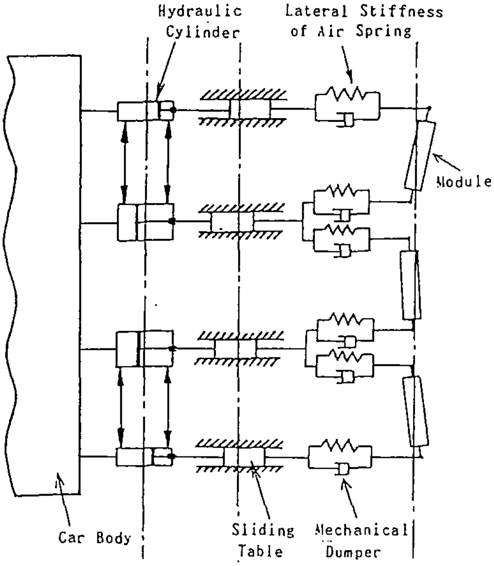

Fig.5

Model of Vehicle Lateral Suspension

There are two types of reaction plates; a steel-aluminum type and a steel-copper type, and the standard clearance of the copper type is larger since electric conductivity of the copper type is larger than that of the aluminum type.

(2) VVVF Inverter and Propulsion Control

A rated output of the VVVF inverter which controls thrust is 1560kVA, and the maximum frequency range 90Hz. Twelve units of LIMs (3S4P connected) are controlled by one unit of an inverter.

Constant current control is adopted with slip frequency fixed to obtain constant thrust.

(3) Braking Control

An electric brake as a main braking system, a regenerative brake and a negative-phase brake are used for braking. When a brake is applied at the speed of about 100km/h, braking current from a motor is consumed by an auxiliary power supply unit on a vehicle, and surplus of the current flows to a conductor system (regenerative current). When the speed becomes more slower, and an inverter frequency goes down in response to the speed, and the phase of a linear motor is reversed (negative-phase brake). Since it is difficult to maintain stopping accuracy only with the negative-phase brake, a hydraulic mechanical brake which clasps rails with brake pads functions to stop the vehicle.

When regenerative current is not obtained and the electric brake is in trouble, the hydraulic mechanical brake is used as an emergency brake.

3.2. TESTING LINE

3.2.1 Track and Structures

A testing line constructed in the southern area of Nagoya city is made up of a 1.5km-long main line which has platforms at both ends and a 80m-long turnout line. The testing line has capacity to conduct test running at the speed of up to 110km/h, and the minimum curvature 100mR and the maximum gradient 7% are provided on the main line so that various characteristics of the vehicle when passing through a sharp curve, a steep grade and a turnout point (the minimum curvature 25mR on the turnout line) can be grasped. A schematic picture of the testing line is shown in Fig. 6.

Various types of structures such as concrete girders, and steel girders of which materials and stiffness are different with each other are used, and various types of attaching methods are provided for test purpose on the track. However, a standard structure is steel-made H-beam ties fixed on simple girder of PC-concrete, and rails are mounted on both ends of the steel-made ties (Fig. 7). The rail is made of steel, and has an inverted-U shaped cross section, and reaction plates are attached on the top of the rails by calking. A substructure of the standard structure is made of RC-pier. A turnout is the 3-joint horizontal revolving type, of which the overall length is 33.2m with change-over time about 15 seconds.

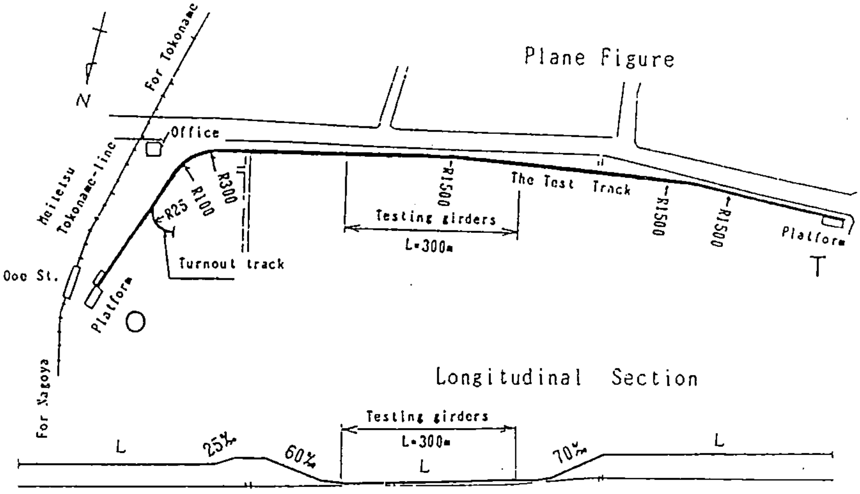

Fig.6 Outline of Testing Line

3.2.2. Power and Signal Equipment

A power equipment which supplies DC1500V to the conductor system is basically the same in terms of structure as a transforming station for conventional railways.

Since the vehicle velocity cannot be calculated from the revolution of axles in case of a levitation system as can be for conventional railways, twist points of parallel two-line induction loop line which are continuously placed along a track are detected with an antenna to locate the position of a vehicle and to detect the velocity. To detect the position of a vehicle, a check-in/check-out type of a induction loop line which has been put to practical use for new transportation systems is adopted. In addition, separately of this induction system, an automatic train stop device is mounted, and it transmits information with transponders and applies emergency braking when the speed excesses its limit.

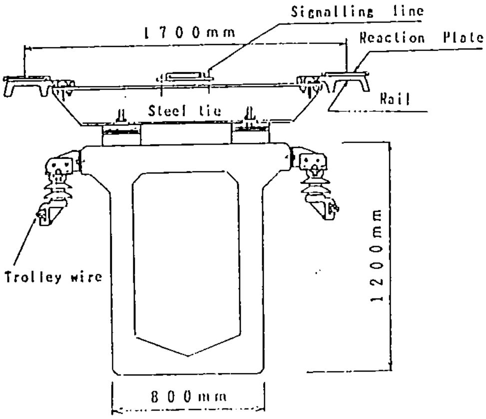

Fig.7

Section of Standard Type Guideway

4. EVALUATION TEST

4.1 Outlines of Evaluation Test

Running tests are planned to be conducted on the testing line for two years from 1991. Major purposes of the running tests are to prove that the HSST-100 system has sufficient safety, reliability and economic efficiency as a public transportation system.

The testing items cover every field from vehicle (a levitation and guidance system, a thrust and braking system), track (including turnout), electric power equipment to a signal and safety system. Main items are high-speed running (the maximum speed about 110km/h), passing through a sharp curve (25mR), running characteristics at passing through a turnout, girder deflection and levitation/guidance characteristics, characteristics against troubles such as drops of magnets, etc.

4.2 Example of Measurement of Vehicle Movement, Vibration and Riding Quality[1)]

Since running tests have been now under way, one of the measured

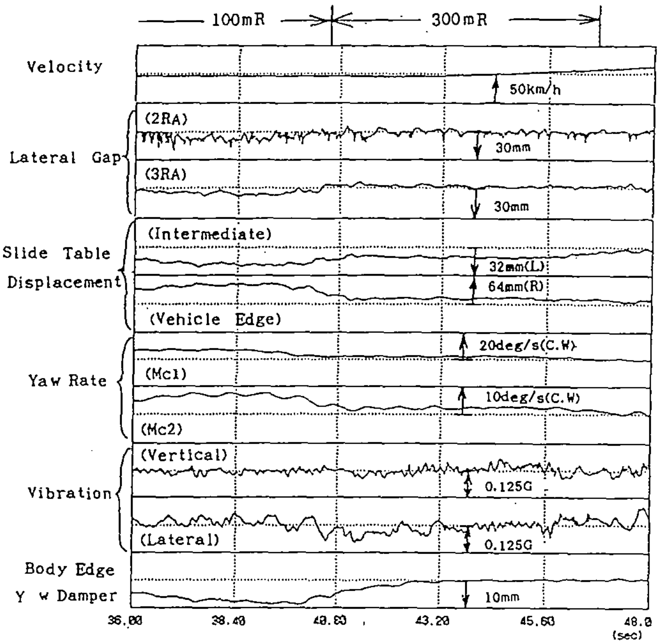

Fig.8 Example of Measured Vehicle Dynamics

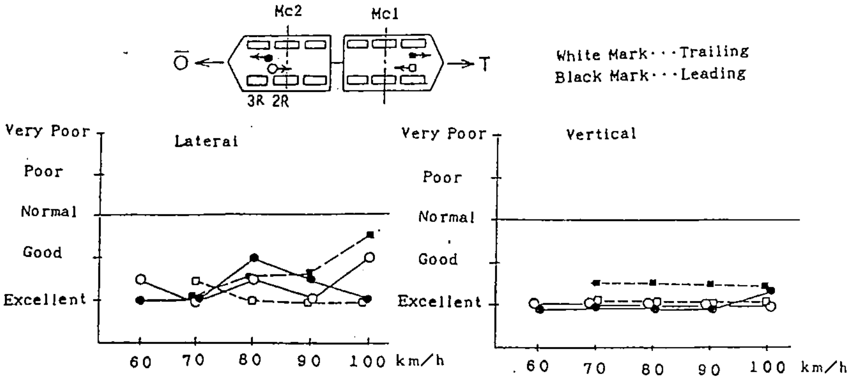

Fig.9 Example of Measured Riding Quality

results concerning characteristics of horizontal vehicle movement and vibration riding quality will be stated as an example here.

Fig. 8 shows measured results of vehicle dynamics when a vehicle passes through curvatures (about 50km/h). In this section of the testing line, a vehicle passes continuously through curvatures with their radius being 100mR and 300mR. With vertical curvatures provided, this section has the most severe line shape in the testing line.

Fig.9 shows riding quality which is calculated based on vibration acceleration on vehicle floor, and riding quality standards of the former Japan National Railways[2] is used for the evaluation. The measured values at the speed of up to 100km/h are in the range of 'very good' and 'good'. Clear influence of speed is not observed.

5. POSTSCRIPT

In this paper we describe on the outline of MAGLEV Urban transportation system HSST-100 and some examples of results of running tests. As we have been carried out various kinds of running tests now, we shall present further reports at another chance.

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