H 16-S-2

3115

OUTLINE AND PERFORMANCE TESTS OF MEDIUM CAPACITY NEW TRANSIT SYSTEM DRIVEN BY LINEAR INDUCTION MOTORS

H.Kanematsu,Ph.D.[1] K.Fukumoto[2] Y.Yoshimoto[2] A.Izuwa[3] K.Takasaki[3] M.Yamaguchi[3]

1)Mitsubishi Heavy Industries, Ltd. Transportation & Airport system Department Machinery Headquarters 5-1 Marunouchi 2-chome, Chiyoda-ku, Tokyo, 100 Japan

2)Mitsubishi Heavy Industries, Ltd. Mihara Machinery Works 5007 Itozaki-cho, Mihara-shi, Hiroshima, 729-03 Japan

3)Mitsubishi Heavy Industries, Ltd. Technical Headquarters Hiroshima Research & Development Center 5007 Itozaki-cho, Mihara-shi, Hiroshima, 729-03 Japan

ABSTRACT

Mitsubishi has developed a medium capacity guideway transit system which is designed to operate above streets in urban districts. The vehicles, driven by linear induction motors and merely supported by steel wheels, feature low environmental pollution [low noise: 65 dB (A)], a small turning radius [30 m] with good maneuverability, and low construction and maintenance costs.

This paper presents an outline of the system and describes performance tests.

INTRODUCTION

Urban transit systems tend to be massive overcrowded networks. Yet the systems absolutely require effective utilization of space and must produce a minimum of environmental pollution, as well as be safe and comfortable. Urban communities are eagerly awaiting a transit system that satisfies not only the above-mentioned conditions, but also meets the demand for low construction and maintenance costs. One such ideal vehicle is a new steel-wheeled linear motor powered transit system, which is in use in Toronto and Vancouver, Canada, and in Detroit, the USA. It is a medium capacity, urban transit system with a high valuation and reliability.

Mitsubishi's New Transit System, Driven by Linear Induction Motors, is moreover improved to meet strict Japanese environmental and special conditions concerning the reduction of noise pollution and so on.

This report describes our new transit system and explains the results of tests executed at EXPO '88 in Saitama, Japan.

Photo.1 Steel-wheeled Linear Motor Powered Transit System in Vancouver

A DESCRIPTION OF OUR NEW TRANSIT SYSTEM

Role in urban transit

In Japan, two types of linear motor cars are well known, the MLU (JR Miyazaki test line) and the HSST exhibited at the Scientific Exhibition in Tsukuba, Japan. Both are electromagnetic levitation, high-speed transit vehicles. Various transit vehicles utilizing linear motors have been developed and are in operation around the world as shown in Table 1 and they may be generally divided into two types: interurban large capacity, high-speed transit, which includes JR MLU and HSST, and urban medium capacity conventional speed systems. Our new transit system, which is of the later type, is a medium capacity guideway transit system supported with steel wheels and driven by linear motors. The rail network is designed to be elevated and installed above streets in urban districts.

Table.1 Transit Systems Driven by Linear Motors

LINEAR MOTOR	SUPORT AND GUIDE	NAME OF THE SYSTEMS
INDUCTION TYPE	ATTRACT ELECTRO-MAGNETIC LEVITATION	HSST (JAPAN) BIRMINGHAM MAGLEV (ENGLAND)
	STEEL WHEEL	UTDC SYSTEM (CANADA,U.S.A.) MITSUBISHI SYSTEM (JAPAN) LINEAR METRO (JAPAN)
SYNCHRONOUS TYPE	REPULSIVE ELECTRO-MAGNETIC LEVITATION	JR MLU (JAPAN)
	ATTRACT ELECTRO-MAGNETIC LEVITATLON	TRANSRAPID (WEST GERMANY)
D.C. TYPE	RUBBER TIRES	ALPS (JAPAN)

Outline

Photo.2 shows a front view of a transit system driven by linear motors.

Unlike conventional railways, with the new vehicles linear motors directly exert driving and braking force, while wheels simply support and guide the truck of a vehicle only.

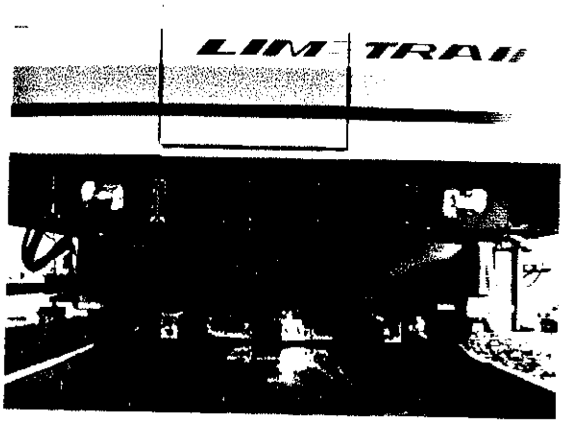

Photo.2 Steel–wheels and Linear Motor

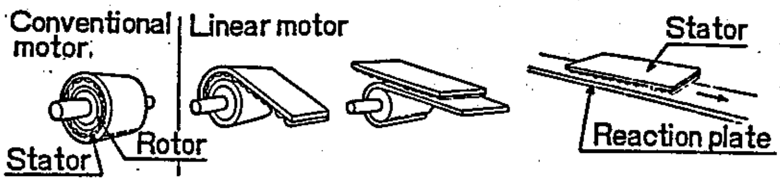

Fig.1 Linear Propulsion System

The linear motor employed in this system, strictly speaking, should be called a Linear Induction Motor (LIM). It is an open, plate like motor (Fig.1) which consists of a platelike stator and a reaction plate.
The stator is mounted on the truck of a vehicle and the part corresponding to the rotor of a conventional motor is laid on the ground as a reaction plate. Conventional motors generate rotational energy, while linear motors generate direct linear motive force.

Features

Linear motors produce following advantages:

(1) Low noise

Direct thrust generated by linear motors makes the reduction gear unnecessary, accordingly no gear noize is caused. No transmission of driving force through the wheels means little abrasion, thereby the sound of the wheels is reduced to a minimum level.

(2) Smooth running on small radius curves (Fig.2)

The wheel axles need not be fixed in a linear motor system. Axles may move with complete freedom, therefore smooth running without squeal noise and wheel slip on small radius curves is possible.

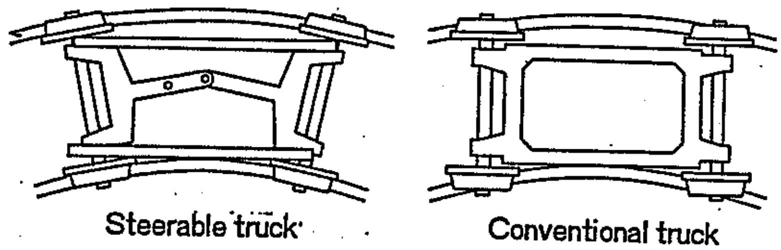

Fig.2 Smooth Running at Small Radius Curves

(3) Ascending on a steep gradient

Motive force is independent of the adhesion between wheels and rails, therefore linear motor cars are able to ascend a steep gradient.

(4) All-weather operation

Stable operation is guaranteed despite weather conditions such as snow. Again, a driving force independent of the wheels permits this operation.

(5) Low construction cost

Construction costs of elevated railroads and tunnels are reduced, since the cars have a light and small body, platelike motors, small-redius wheels and no reduction gear. Linear motor cars are able to run on a smaller redius curve and a steeper gradient than conventional motor cars, thereby track-layout plans are more flexible.

(6) Low maintenance cost

Linear motors have no rotating parts, and small abrasion of wheels and rails further reduces maintenance cots.

As mentioned above, the linear motor systems described meets the needs of urban transit systems.

THE NEW MITSUBISHI TRANSIT SYSTEM DRIVEN BY LINEAR INDUCTION MOTOR

New linear motor transit systems, which have the various benefits mentioned above, are in practical use in Canada and the USA, and are regarded as valuable and reliable medium capacity urban transit systems. For use in Japan, however, there are unsolved problems, such as operating the system in the extremely limited space of streets, and the observance of strict regulations concerning environmental noise.

The New Mitsubishi Transit System Driven by Linear Induction Motors is a system which solves such problems. It has two unique features, low noise and a high performance truck.

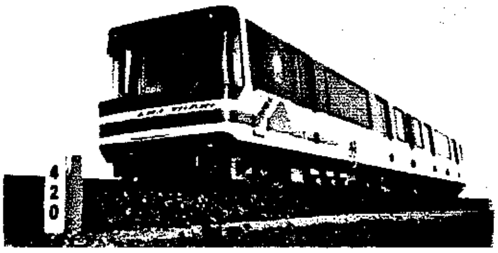

Photo.3 Mitsubishi Transit System Driven by Linear Motor

Low noise

In Japan, the noise level of elevated transit systems constructed in an urban space should be less than 70 dB (A) at a distance of 10 m away from the center of the track.

The noise level of this system is 63 - 65 dB (A), thereby it sufficiently satisfies the index.

High performance truck

Train chasis must pass through 25 m wide intersections for use over Japanese streets. For this purpose, they must be able to negotiate sharp curves 30 m in radius, without squeal noise.

Our new transit system employs a high performance truck to realize this requirement, and even permits stable high-speed operation around relatively sharp curves, contrary to typical performance expectations for these types of vehicles on small radius curves. And the system will adequately meet lay-out flexibility requirements demanded with Japanese urban transit systems.

Below is an outline of investigations and examinations conducted to improve performance of the vehicles.

PERFORMANCE IMPROVEMENTS

Reduction of noise

Noise investigation

Noise from the new linear motor transit system in practical use in Vancouver was investigated to utilize as a base data for reducing noise.

Method of noise level estimation

On the basis of noise investigations, we established procedures to estimate operating noise on elevated track as given.

(1) Sound sources

Noise sources on a girder:

sound from rolling contact of wheels and rails, sound generated by the linear motors, and noise caused by auxiliary equipment mounted on the body .... point source (one for each truck)

Sound radiated from the girder structure:

sound generated from the girder structure of an elevated track .... linear source

(2) Basic equation

The noise (SPL_c) at the point of noise estimation C is expressed by

$$SPL_c = 10\log\left[10^{\frac{SPL_{c1}}{10}} + 10^{\frac{SPL_{c2}}{10}}\right]$$

Where,

SPL_{c1}: noise contributed from track and vehicle interaction

SPL_{c2}: noise radiated by the girder structure

Assuming that the track-vehicle and girder noise are denoted by PWL_1 and PWL_2, respectively,

$$SPL_{c1} = \underbrace{(PWL_1 - 11 - 20\log\overline{AC})} - \underbrace{\left[5 + 20\log\frac{\sqrt{2\pi\,|N|}}{\tanh\sqrt{2\pi\,|N|}}\right]}$$

Contribution from point sources decreasing with distance — Noies reduction caused by deffraction of the parapets

$$SPL_{c2} = PWL_2 - 8 + \underbrace{10\log\left[\frac{1}{d}\tan^{-1}\frac{L}{2d}\right]}$$

Contribution from linear sources decreasing with distance

Where,

$\overline{AC}$: distance between the point source A and the observing point C

N : Fresnal number

L : length of a line source (the length of a vehicle)

d : distance between the linear source and the observing piont C

Measures to reduce noise

In keeping with the above investigation and estimation procedure, the following measures are planned.

(1) Improvement of brake system

The matching of regenerative and disk brakes has been improved to prevent the slip of wheels and to suppress one-sided abrasion.

(2) Improvement in torsional vibration of wheel axles

To suppress the slip of wheels on the rails, taking into consideration the interaction between wheels and rails, the optimum torsional vibration of the wheel axles is determined to prevent the wave-like wear of rails caused by the vibration of axles.

(3) Installation of parapets

Most of the sound is caused by rolling of wheels on rails. Noise on a girder is suppressed by the diffraction effect of the parapets.

(4) Employment of vibration-proof sleepers

To reduce the noise radiated from girders of elevated tracks, rail sleepers are supported by a vibration-proof means, namely the insertion of rubber pads, to suppress vibrations from the track.

The noise of the level applied with the above measures is estimated at 65 dB (A) at a typical point of estimation, a distance of 10 m away from the track center and 1.2 m above the ground.

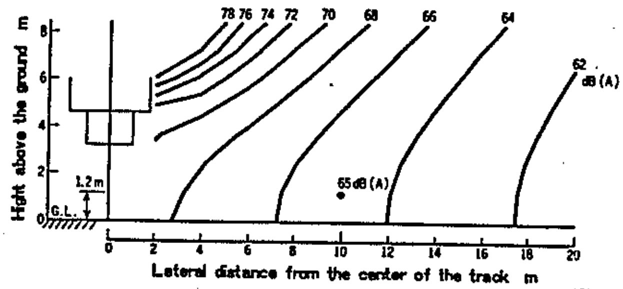

Fig. 3 Noise Estimation (60km/h, 2Vehicles)

High performance truck

Simulation model

Simulated vehicle operations were performed to assess the performance of the truck.

Forces acting on components are divided roughly into the following:

① Excess centrifugal force
② The force acting between wheels and rails (including nonlinear creeping force)
③ Friction between wheels and side frames, and that between side frames and bolster frames.
④ Restoring force of springs and damping force of dampers

The following model, using 29 degrees of freedom (Fig.4), was analyzed, concentrating our attention on the behavior of a steering mechanism.

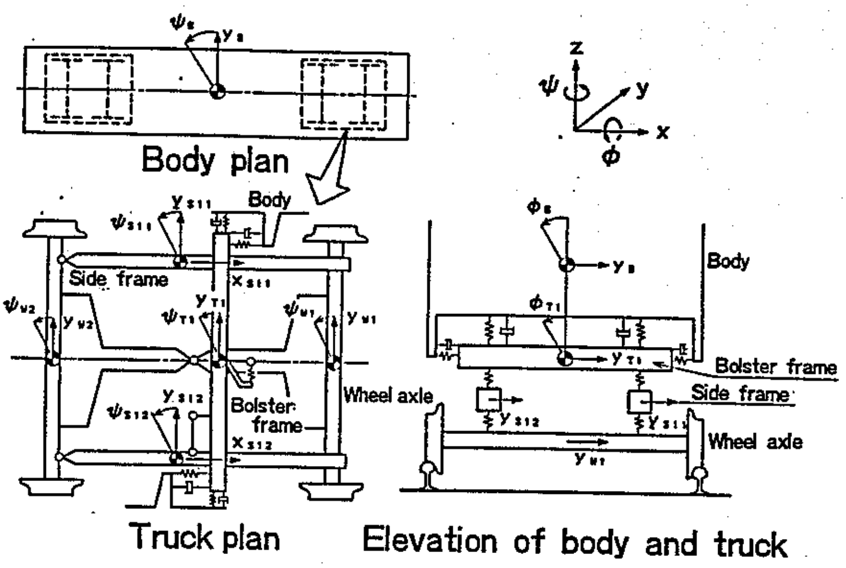

Fig.4 Simulation Model

- Wheel axles (2 degrees of freedom x 4)
  Lateral deviation: y_{wj}, yaw angle deviation: ψ_{wj} (j = 1 - 4)
- Side frame (3 degrees of freedom x 4)
  Lateral deviation: y_{sik}, yaw angle deviation: ψ_{sik},
  Longitudinal deviation: x_{sik} (i = 1, 2, k = 1, 2)
- Bolster frame (3 degrees of freedom x 2)
  Lateral deviation: y_{Ti}, yaw angle deviation: ψ_{Ti},
  roll angle deviation: ϕ_{Ti} (i = 1, 2)
- Body (3 degrees of freedom)
  Lateral deviation: y_B, yaw angle deviation: ψ_B,
  roll angle deviation: ϕ_B

In the above notations, i=1 represents the former truck i=2 the latter truck, j the respective axle, k=1 the left side and k=2 the right side.

The equation describing the motion of the cars, in terms of these forces, is expressed by

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\}$$

Where,

[u] : deviation vector

$\{u\}^T$: $\{y_{w1}, y_{w2}, y_{w3}, y_{w4}, \psi_{w1}, \psi_{w2}, \psi_{w3}, \psi_{w4},$
$y_{s11}, y_{s12}, y_{s21}, y_{s22}, \psi_{s11}, \psi_{s12}, \psi_{s21}, \psi_{s22},$
$x_{s11}, x_{s12}, x_{s21}, x_{s22}, y_{T1}, y_{T2}, \psi_{T1}, \psi_{T2},$
$\phi_{T1}, \phi_{T2}, y_B, \psi_B, \phi_B\}$

[M] : mass matrix

[C] : damping matrix

[K] : stiffness matrix

{F} : external force vector

The equation is solved using Runge-Kutta-Gill's method.

Improving performace

To apply the system to a limited urban space, the train must be able to run smoothly on 30 m radius sharp curves. For this reason, the following measures were employed to improve the performance of the truck.

An axial steering mechanism is utilized, thereby trucks are able to run on a curve without any attack angle. However, the inner and outer circumference of a curved track is significantly different, and inner and outer wheels must rotate at different speeds while travelling around the corners; therefore, slip occurring between wheels and rails causes noise and abrasion of wheels and rails. Hence it is exceedingly important to allow precise rolling. For this purpose, the following measures are adopted.

(1) Sharp sloped wheel tread

Wheels do not sit-flat on top of the track surface, rather, they are angled to promote better guiding and rolling characteristics. Steep 1/9 grade of the wheels allows for different rotational speeds between left and right wheels (for non-slip rolling) on sharp 30 m radius curves.

(2) Use of rails with an asymmetrical cross-section

Rails with an asymmetrical cross-section which permit slack are employed to compensate for the difference between left and right wheels.

The above measures permit left and right wheels to run on a 30 m radius sharp-curve with perfect rolling. Stability during high-speed travel might, however, be reduced, as meandering might occur. The Shinkansem trains employ a reduced grade of 1/40 to maintain stability of high-speed running. To solve the problem of meandering, the following measures were employed.

(3) Stabilizing spring for steering

Non-linear springs were applied between front and rear axles to maintain stability during high-speeds.

The effect of the above measures were examined in simulation runs.

Fig.5 (a) shows the steering angle during a sharp curve with a radius of 30 m. The steering of steerable truck is almost ideal, i.e. perfect rolling.

Fig.5 (b) shows the steering angle of wheel axles effected by an impulse-like external force in a lateral direction, which was equivalent to a warp in the rails of a straight track at a high speed of 80 km/h. The steering configuration converges rapidly and stabilizes (zero steering angle) without any diverging tendency.

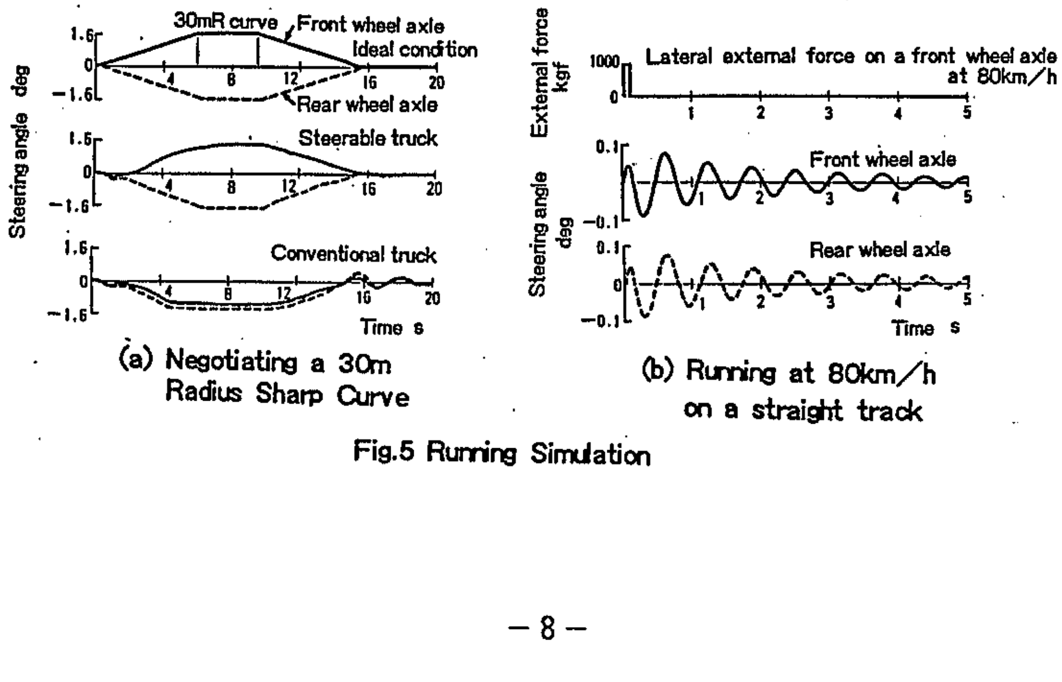

Fig.5 Running Simulation

In this way, we developed a high performance truck capable of running on sharp curves with stability at high-speeds.

PERFORMANCE TEST

For examining the above performances, a test track was constructed at the EXPO '88 site in Saitama (at Kumagaya City, Saitama Prefecture, Japan) during the period January 5th - June 10th, 1988 and various operating tests were carried out with the first trial trip by visitors in Japan (about 350 thousands visitors; A total test length of about 11,000 km). The following is an outline of the test track and the results of the tests.

Outline of test track

The test track was a 850 m rail line including a sharp curve with a 30 m radius, various other curves, a steep incline of 6%, and an elevated guideway.

Fig.6 shows the layout of the test track. For planning the layout, the following conditons were considered necessary in order to verify the major performances of this transit system.

(1) A 30 m radius curve was constructed to verify performance on sharp curves, especially to allow passage through a 25 m wide intersection.

(2) The speed on the test track is maintained at 60 km/h to verify low noise and stability of high-speed operation.

(3) To keep a large space as possible under the girder (4.7 m for practical tracks), the height of the girders was set at 3.2 m (the height of rails 5.0 m) to permit realistic noise measurements for elevated construction, such as construction above streets in an urban district.

(4) The steepest gradient was a 6% slope 26 m in length, which is of greater length than two car bodies (25 m) to verify the performance on steep inclines.

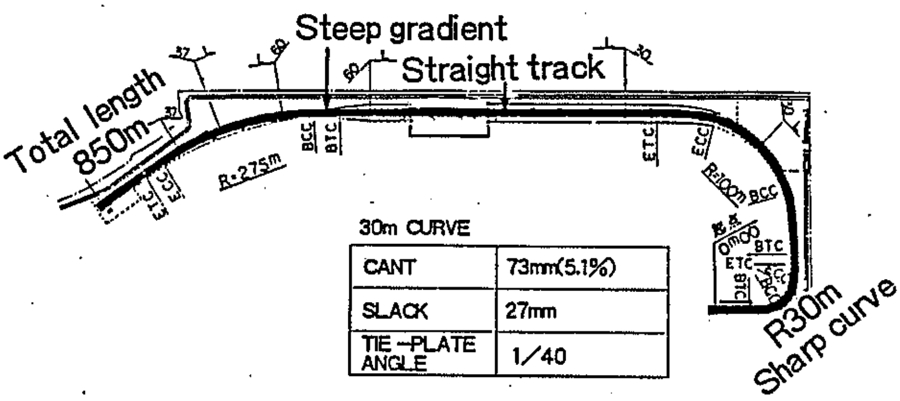

Fig.6 Outline of the Test Track

Outline of vehicle

Photo. 4 and 5 show the outlines of the vehicles and their truck, and Table 2 shows specifications for the vehicles.

The vehicles are driven by linear induction motors mounted to the truck and controlled by a VVVF (variable voltage, variable frequency) inverter.
The vehicles are supported by small radius steel wheels and rails and are guided by the trucks using a semi-forced steering system.
The train is designed as a fixed two-car-unit.

The linear motors have an power output of 65 kW (one-hour rating) and are fixed to the yokes of trucks at three points. The height can be readily adjusted to keep the gap between the motor and the upper surface of the reaction plate. (The standard gap is 11 mm.) Photo.6 is an external view of the linear motor.

Photo.4 Test Vehicles in a 30m Radius Curve

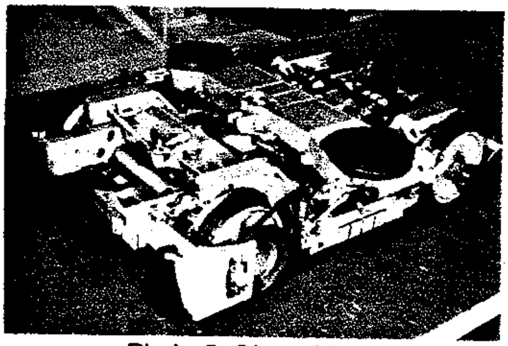

Photo.5 Steerable Truck

Table.2 Specifications of the vehicle

	Items	Specifications
Dimensions	Body (Length x Width x Height)	12.5x2.48x3.02m
	Distance between trucks	8.6m
	Distance between axles	1.7m
	Dia. to wheel	0.52m
	Gauge	1.435m
	Passenger capacity	105 passengers per vehicle
Weight	Dead load	About 15.0t per vehicle
	Max axial weight	Under 7.5t per axle (without power)
Performances	Acceleration	3.2～3.5km／h／s
	Deceleration	3.5km／h／s in usual, 4.5km／h／s in emergency
	Max speed	60km／h
	Smallest passable radius	30m
Systems	Truck system	Semi-forced wheel-axle, Two axle bogie truck
	Feeding system	DC750V Rigid body feeding and earth-return circuit
	Operation system	Manual operation
	Driving system	Linear induction motor system
	Control system	VVVf inverter system
	Brake system	LIM regenerating brake, Direct at brake and electromagnetic attraction brake

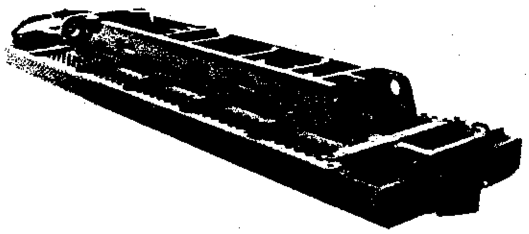

Photo.6 Outline of a Linear Induction Motor

Items	Specifications
Type of rating	1 hour
Rated voltage	AC3ϕ 550 V
Rated frequency	22 Hz
Rated current	195 A
Outpwt power	65 kw
Number of poles	8 P
Overall length	Approx. 2270 mm
Overall width	Approx. 630 mm

Items and conditions of the tests

A variety of tests were performed to verify the practicality of our system for urban transit.

Wheel noise was measured during operation on elevated track at a speed of 60 km/h. The vibration of the bodies and trucks, steering conditons of wheel axles, and wheel load and transverse pressure were monitored while negotiating small radius curves and running straightly at a high speed.

Test results

Our system performed adequately during operational test and trial runs with passengers, meeting the requirements of an urban transport vehicle.
The following are results of major test items.

Noise

Fig.7 shows the noise level at N1 (10 m away from the center of the track, 1.2 m above the ground).

The noise level at 60 km/h was 63 - 65 dB (A), sufficiently lower than the maximum allowable value in Japan of 70 dB (A). This test confirmed that our units satisfied low noise performance levels.

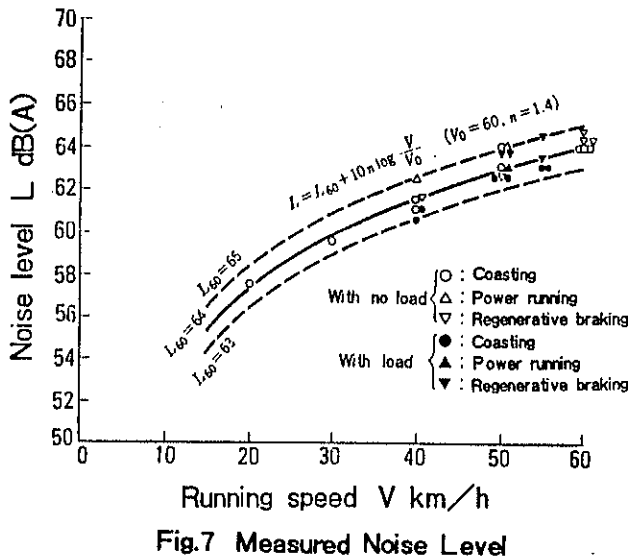

Fig.7 Measured Noise Level

The noise level of our system is compared with the noise of various transportations in Fig.8. It is obvious that our new transit system driven by linear motors is quieter than any othervehicles.

As mentioned above, our new rail system is adaptable to the Japanese strict environmental standard as well as our rubber tired monorail system which is operated in Chiba, Japan.

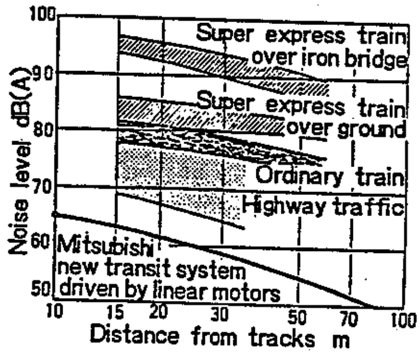

Fig.8 Noise Level of Various Transportations

Noise levels increase occurred with higher speeds (Fig.7), expressed by the following equation.

$$L = L_{60} + 10n\log\frac{V}{V_0}$$

L : noise level at N1 dB (A)
L_{60}: noise level at N1 on running at a speed of 60 km/h dB (A)
V : running speed km/h
V_0 : standard running speed, namely 60 km/h
n : power index, namely 1.4

Noise levels increase by 1.5 dB over coasting noise when accelerating from medium-speed travel and when regenerative braking is effected during high-speed. This is caused by noise generated by the linear induction motor.

In 1/3 octave bands, the noise level reaches a highest value at 630 Hz and 800 Hz. The increase in the 160 - 250 Hz component, during regenerative braking and power running, is caused by sound from linear motors controlled by a VVVF inverter.

The 630 Hz and 800 Hz components are more significant overall, an effect of the steel wheels which have a broad peak at 500 - 1000 Hz.

The results of noise tests revealed that the major source of noise is the rolling of the wheels on the rails. The sound of the motors also becomes a major noise source during transition from low or medium-speed coasting to power running and that from high-speed running to regenerative braking. It has also been verified that noise generated from elevated girders is small.

<u>Vibration</u>

The vibration of the body is very small, a maximum of 0.08 G^{0-P} laterally, 0.08 G^{0-P} vertically, and 0.06 G^{0-P} longitudinally. These values correspond to a very comfortable ride.

The vibration of the truck is measured to be 1.1 G^{0-P} on the bolster frame and 5.4 G^{0-P} on the axle box, at maximum, which are much smaller than those of conventional trucks.

Vertical vibration of rail sleepers is 1/2.4 and that for the upper surface of the elevated girders is 1/560, where the vertical vibration of the rail is normalized to be unity. These values represent very small transmission of vibration from the rail to the elevated girderage, a result of the vibration-proof rail sleepers.

Steering ability and stability at high speed

Fig.9 shows the measured steering angle of axles at a maximum speed of 60 km/h over the entire length of track. The steering angle in a 30 m radius sharp curve was measured to be 3.1 deg, which is almost equal to the ideal steering angle (no attack angle) of 3.2 deg. It has been confirmed that the train is capable of smooth operation without squeal noise.

On the other hand, the steering angle while running on a straight track at a high speed(60km/h) is approximately zero and stable. This measurement represents the stability in high-speed travel on a straight track.

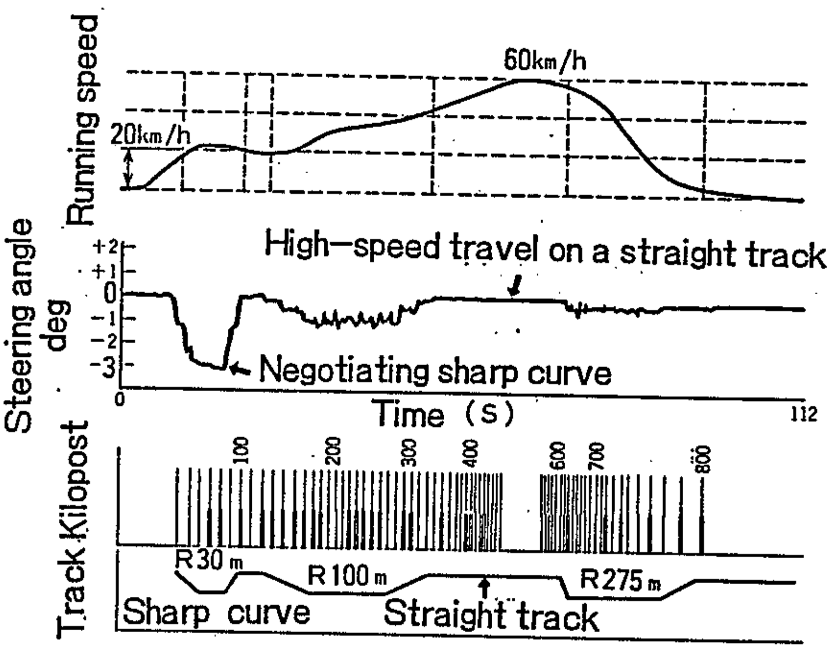

Fig.9 Measured Steering Angle

The above steering ability and stability was confirmed by four CCD cameras attached to the truck observing positions of wheels with respect to rails, too.

Conclusion

The New Mitsubishi Transit System Driven by Linear Induction Motors was examined on a test track. The results of tests showed several superior features, especially low noise, running ability on sharp curves, and the stability of operation at high speed. It was verified that our new rail system is appropriate as an urban transit system.

OUTLINE AND PERFORMANCE TESTS OF MEDIUM CAPACITY NEW TRANSIT SYSTEM DRIVEN BY LINEAR INDUCTION MOTORS

Masahiro Yamaguchi

Urban transit systems tend to be massive overcrowded networks. Yet the systems absolutely require effective utilization of space and must produce a minimum of environmental pollution, as well as be safe and comfortable. Urban communities are eagerly awaiting a transit system that satisfies not only the above-mentioned conditions, but also meets the demand for low construction and maintenance costs. One such ideal vehicle is a new steel-wheeled linear motor powered transit system, which is in use in Toronto and Vancouver, Canada, and in Detroit, the USA. It is a medium capacity, urban transit system with a high valuation and reliability.

Mitsubishi's New Transit System, Driven by Linear Induction Motors, is moreover improved to meet strict Japanese environmental and special conditions concerning the reduction of noise pollution and the truck steering ability and stability.

This report describes our new transit system and explains the results of tests executed at EXPO '88 Saitama, Japan.

Section 1 describes an outline of new transit systems driven by linear motors. Section 2 mentions the background of development and features of Mitsubishi's New Transit System Driven by Linear Motors. Section 3 refers to the investigations of performance improvements i.e. reduction of noise and a high performance truck. Section 4 reports the results of performance tests at EXPO '88 test track.
Among the major conclusions:

(1) LOW NOISE: The noise level at 10 m away from the center of the track in operating at 60 km/h was 63-65 dB (A), sufficiently lower than the maximum allowable value in Japan of 70 dB (A), by means of installation of parapets, vibration-proof sleepers and so on.

(2) STEERING ABILITY ON SHARP CURVES: It has been confirmed that our new transit system is capable of ideal smooth operation in a 30 m radius sharp curve without squeal noise, by means of adoption of steerable trucks, sharp sloped tread wheels and asymmetrical cross-section rails.

(3) STABILITY OF OPERATION AT HIGH SPEED ON STRAIGHT TRACKS: We confirmed that our improved steerable truck is capable of stable operation at high speed (60 km/h) on a straight track by measurements of steering angle and observation of positions of wheels with respect to rails.

As mentioned above, it has been confirmed that Mitsubishi's New Steel Wheeled Linear Motor Powered Transit System is adaptable to strict Japanese environmental and space-limited conditions.