Automated People Mover System "Crystal Mover" for Singapore's LTA

HIROYUKI MOCHIDOME
MASAHISA MASUKAWA
YASUYUKI SUZUKI
MAKOTO KASHIWA
SHINICHI SADAMITSU
HIROYUKI KOUNO

Mitsubishi Heavy Industries, Ltd. (MHI) has received an order for a rubber tired automated people mover (APM) system from the Land Transport Authority (LTA) of Singapore, and has made its first delivery of the originally developed "Crystal Mover" APM vehicles. The "Crystal Mover" is an export version conforming to overseas market needs, excellent in design, and people- and environment-friendly. For installation in Singapore, the standards and specifications can be varied depending on the wishes of customers. This paper reports on the "Crystal Mover" and its subsystems that assure safe and comfortable operation.

1. Introduction

In East Asian and Southeast Asian nations, there has recently been an urgent need for convenient urban traffic services against the background of rapid urbanization. At the same time, reduction of environmental load is a global issue. These nations are promoting construction of guideway traffic systems, including subways and new transit systems. MHI received an order for the automated people mover (APM) system for the Seng Kang and Punggol new town from the Land Transport Authority (LTA) of Singapore. The Seng Kang Line was opened in January 2003, and manufacture of vehicles and construction of system are in progress for start of operation of the Punggol Line in 2004. This paper gives an outline of the APM vehicle of the system and its subsystems assuring safe and comfortable operation.

2. Outline of APM system

The APM system for Singapore's LTA is a feeder line from Seng Kang Station and Punggol Station of a new subway North-East Line to New Town. Both the Seng Kang Line and the Punggol Line are formed of two east and west loop lines which converge at a subway junction station. The Seng Kang Line is 10.69 km long with 14 stations, and the Punggol Line is 9.47 km long with 15 stations. The design transport capacity of the system is 2 100 PPHPD (passengers per hour per direction) in the Seng Kang Line and 2 700 PPHPD in the Punggol Line.

This APM system, which is based on Japan's new transit system, consists of the vehicles and subsystems shown in **Table 1**.

Vehicles run by full-automatic driverless operation

Table 1 Composition of APM system

Subsystem	Principal component	Function
Vehicle	Vehicle	Transport unit
Operation control unit	Operation control unit	Operation and management of total system
Signaling system	AVP/VD device	Signaling and safety function
Communication system	LCX transmission device	Communication between wayside and vehicle
Automatic operation system	On-board AVP/AVO device, station AVO device	Automatic operation of vehicle
Power distribution system	Transformer, power rail	Supply of electric power to system and vehicle
Guideway	Running surface, guide rail, switch	Vehicle running line
Station facilities	Fare collection system, passenger information device	Fare collection, passenger information service
Maintenance facilities	Depot, maintenance equipment	Vehicle maintenance facilities

(Note)

AVP/VD: Automatic Vehicle Protection/ Vehicle Detection
AVP: Automatic Vehicle Protection
AVO: Automatic Vehicle Operation

with automatic train control (ATC). The ATC is composed of automatic vehicle protection (AVP), automatic vehicle operation (AVO), and automatic vehicle supervision (AVS). The AVP supports safe operation of vehicles such as signaling safety equipment. The AVO controls automatic operation of vehicles. The AVS has functions of operation command, operation monitoring and operation recording of the system.

3. Development of APM vehicle

3.1 Outline of APM vehicle

The APM is a rubber tired vehicle. Carrying 105 passengers per vehicle, the driverless system is operated fully automatically. The outline drawing of vehicle is shown in **Fig. 1** and its main specifications are given in **Table 2**.

This APM vehicle has been newly developed for overseas markets on the basis of the technology of MHI's new rubber tired transportation system. To meet varied transport needs flexibly, as compared with existing vehicles, the size and speed have been increased, and the single-car configuration is achieved. A prototype vehicle was fabricated, the basic performance and functions were verified, the interior and exterior design were proposed for the Singapore project, the customer's desired specifications were incorporated in the product, and mass production was designed.

The principal and new design items of the vehicle are discussed below.

3.2 Vehicle aesthetic design

The vehicle is the system's core and also its face. The vehicle aesthetic design (interior and exterior) is vital for passengers' first impression of the vehicle and the system. Today, the vehicle aesthetic design is an impor-

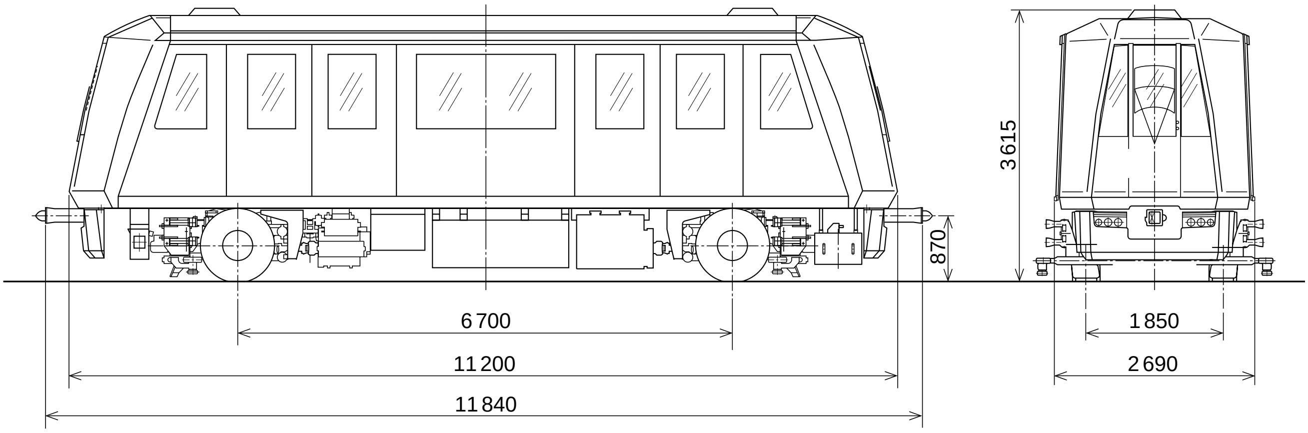

Fig. 1 Vehicle configuration

Table 2 Vehicle specifications

Item	Specification
Configuration	Single-car
Capacity (passengers)	105 (including 18 seats)
Vehicle mass (t)	14.9/vehicle
Vehicle dimensions (mm)	11 840 long x 2 690 wide x 3 615 high
Guide system	Side guide two-axis four-wheel steering system
Electric system	750 VDC
Gauge (mm)	Gauge 1 850, guide rail span 3 200
Vehicle performance	Maximum speed ・Vehicle performance: 80 km/h ・Operation: 70 km/h Acceleration: 1.0 m/s^2 (3.6 km/h/s) Deceleration ・Maximum service: 1.0 m/s^2 (3.6 km/h/s) ・Emergency: 1.3 m/s^2 (4.7 km/h/s)
Carboy structure	Aluminum alloy welded structure
Traction motor	Three-phase induction motor, continuous rating 80 kW x 2 units
Propulsion control system	VVVF inverter vector control (individual control of each axis) (with variable load control and regenerative brake)
Brake system	Electric command pneumatic brake with regenerative brake (with stand-by brake and parking brake) (with variable load control and wheel slide prevention control)

tant element for enhancing the commercial value and differentiating it from other vehicles.

Against this background, the development of this APM vehicle was participated in by industrial designers outside of MHI, and the job was consigned to a design team from proposal to supervision of the vehicle design. In cooperation with industrial designers, efforts were concentrated on both ideal design and productive function and performance, and this APM vehicle was awarded the Minister Prize in the 32nd Machine Industrial Design Competition in Japan.

3.2.1 Design concept

The concept of the vehicle aesthetic design is based on the idea that this APM vehicle embodies the strategy for transportation system export of the future. The keyword of the design is "Crystal." This has the concepts of Universal (common and general throughout the world), Distinctive (different from others), Futuristic (forward-looking), and Diamond-like (lasting for ever). In line with this design concept, the vehicle was named "Crystal Mover"; the trademark has been registered and is being strategically advertised as a new product brand.

3.2.2 Exterior design

The exterior design is intended to embody the crystal image of the vehicle. In particular, the nose is a dynamic polyhedral profile making use of features of the APM vehicle such as that no driver's cabin is required because operation is driverless. The sides are not flat but have a delicate three-dimensional curve to soften the sharp image of polyhedron, and a refined urban feeling is achieved. The car body is painted in pearl white and indigo blue, the window is harmonized in design, and a brilliant novel style is presented.

3.2.3 Interior design

The interior design is a fusion of the design concept and the required functions of the cabin. Information for passengers is provided in the corners of the cabin, and the visual recognition and function are enhanced. Specifically, as we face toward the front of the vehicle, the line map and other operation service information are shown in the left side corner, while the right side corner is for emergency information, including the emergency stop button, emergency notice system, and related caution and warning labels. In addition, an LCD information display device is installed in each corner. The cabin graphic design is a harmonious blend of customer requirements and designer ideas.

The cabin's side panels and ceiling are white, and the floor is gray. The seats are grayish blue, and the handrails and grip bars are accentuated with a wine color. This color scheme, which avoids metallic tones of white or gray, creates bright and friendly image for the cabin.

A view of the cabin is shown in **Fig. 2**.

Fig. 2 Cabin interior

3.3 Ride quality

The vehicle ride quality is determined by its vibration transmission characteristics and the irregularity (in quantity and wavelength) of the running surface. To realize comfortable ride quality, the vibration and vehicle ride quality were analyzed in consideration of the irregular properties of the running surface. The design of vehicle vibration transmission characteristic was optimized, optimum installation and management of running surface irregularity were executed, and good ride quality has been realized.

Concept of analysis for vibration and ride quality of vehicle is shown in **Fig. 3**.

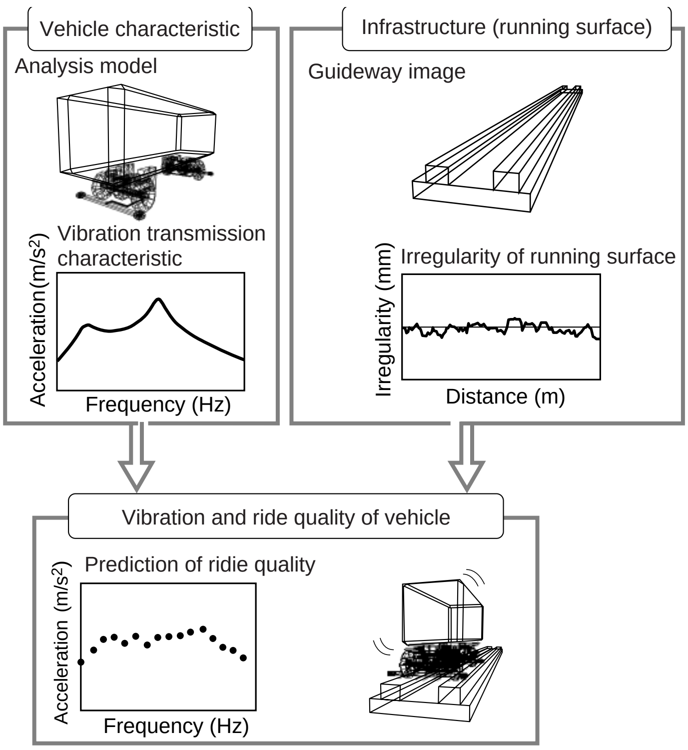

Fig. 3 Concept of analysis of vibration and ride quality of vehicle

3.4 Vehicle crashworthiness

In the railway and guideway transportation system, collision of vehicles is prevented by the signaling system, but in recent overseas projects, there has been an increasing demand for vehicle crashworthiness aside from the requirement for the signaling system. In this

APM vehicle, it was required that in the event of collision of vehicles, the space between cabins should not collapse and the collapse distance should not exceed one meter.

Vehicle crashworthiness is a new technical field that is not established sufficiently in vehicles of the railway and guideway transportation system. In this Singapore project, the latest automobile crashworthy technology and design techniques have been introduced and adopted.

Essential points of crashworthy design are discussed below.

3.4.1 Collision conditions and design target

In the APM system, collision of vehicles is prevented by the signaling system, and it was attempted to set target values of collision conditions guaranteed in the vehicles and crashworthiness that matched the safety performance of the entire system. These items are summarized in **Table 3**. As shown in the table, it was deduced that collision of vehicles could occur due to human error only in the case of limited manual operation. Target values were determined by matching them with the required specifications related to crashworthiness, vehicle basic specifications, and structural design conditions.

3.4.2 Scenario of collision energy absorption

To assure safety in a collision, it is important to absorb the collision energy adequately and reduce its impact. **Fig. 4** shows a scenario of absorption of collision energy. The collision energy is absorbed by the shock absorber of the coupler and the collision energy absorbing mechanism provided in the carbody (mechanical fuse described below). In particular, in the event of a collision that exceeds the buffering capacity of the coupler, the two carbodies collide with each other, the collision energy absorbing mechanism provided in the front end of the carbodies is deformed and collapsed, the collision load is suppressed below the specified value, and the collision energy is absorbed uniformly and stably.

3.4.3 Collision energy absorbing mechanism

It is difficult to build a collision energy absorbing mechanism of the carbody structure and optimize the carbody structure while complying with other structural design requirements. In this APM vehicle, therefore, a separate collision energy absorbing mechanism (mechanical fuse) is attached to the carbody structure. This mechanical fuse, based on a device developed by Mitsubishi Fuso Truck & Bus Corporation for use in a

Table 3 Vehicle collision condition and design target

Item		Specification
Collision condition	Operation condition	Manual operation with protection by on-board AVP
	Collision condition	Face to face collision of two vehicles of same mass and at same speed
	Vehicle mass upon collision	Vehicle mass with normal capacity of passengers
	Collision speed	11 km/h
	Bias condition	Vertical direction offset Lateral direction offset In consideration of diagonal collision on curve
Design target	Collapse distance	Not more than 0.5 m in nose of vehicle Not reaching into cabin
	Absorption energy	110 kJ or more
	Impact force upon collision	300 kN or less

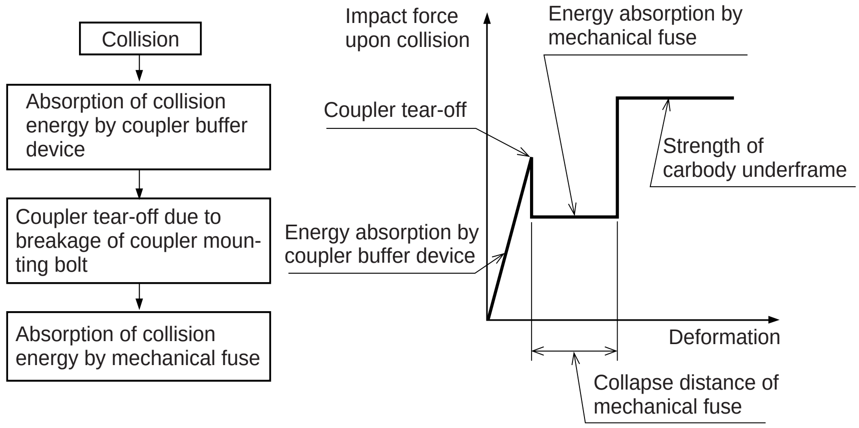

Fig. 4 Scenario of absorption of collision energy

nuclear fuel transport truck, is a perforated conical steel tube structure. In its mechanism, the tube buckles and deforms due to the collision load applied to the front end, and hence absorbs the collision energy (**Fig. 6**).

Two mechanical fuses are provided under the front end of the carbody. The front end structure of the carbody has directivity in deformation and collapse mode by perforation so as to maintain strength against normal load and be likely to collapse against collision load.

3.4.4 Design and verification of crashworthy mechanism

Fig. 5 shows the general flow from design to verification of the collision energy absorbing mechanism for the APM vehicle.

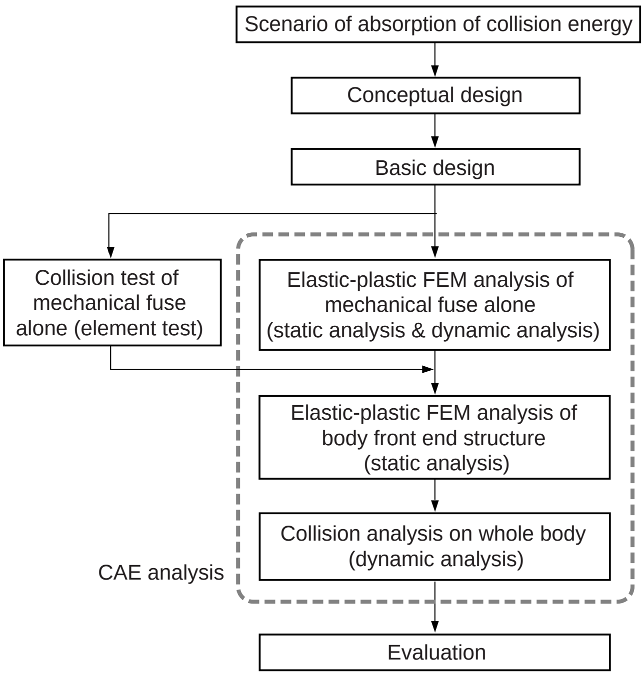

Fig. 5 Design flow of collision energy absorbing mechanism

Following the basic design, the mechanical fuse was evaluated by CAE analysis and element testing to execute detail design and verification at the same time. Analysis and element test are executed repeatedly at each step and the design is improved until the initial aim is satisfied. As for the mechanical fuse, collision test of the fuse was executed, and dynamic collapse characteristics and buckling mode were verified. Fig. 6 shows comparative analysis and test results of the fuse in the deformation mode. As shown in Fig. 6, the analysis and test results coincide well in the deformation mode. Regarding the collision energy absorbing characteristics, the analysis and tests results also coincide very well, and the design target is satisfied. The mechanical fuse was thus shown to have the designed collision characteristics, and the validity of CAE analysis was also verified.

Finally, the whole vehicle provided with mechanical fuses was evaluated for its collision characteristic. Only that which had been already confirmed to be valid was verified by the CAE analysis, and no test with the actual vehicle was conducted. **Fig. 7** shows the analysis results of face to face collision in a straight line. As shown in the figure, the collapse distance of the vehicle structure after collision is 0.27 m, which satisfies the design target of 0.5 m.

Stable deformation and collapse were also confirmed. Diagonal collision on a curve was also evaluated by CAE analysis, and favorable results were obtained.

Thus, the collision energy absorbing mechanism for the vehicle was designed and verified by effectively uti-

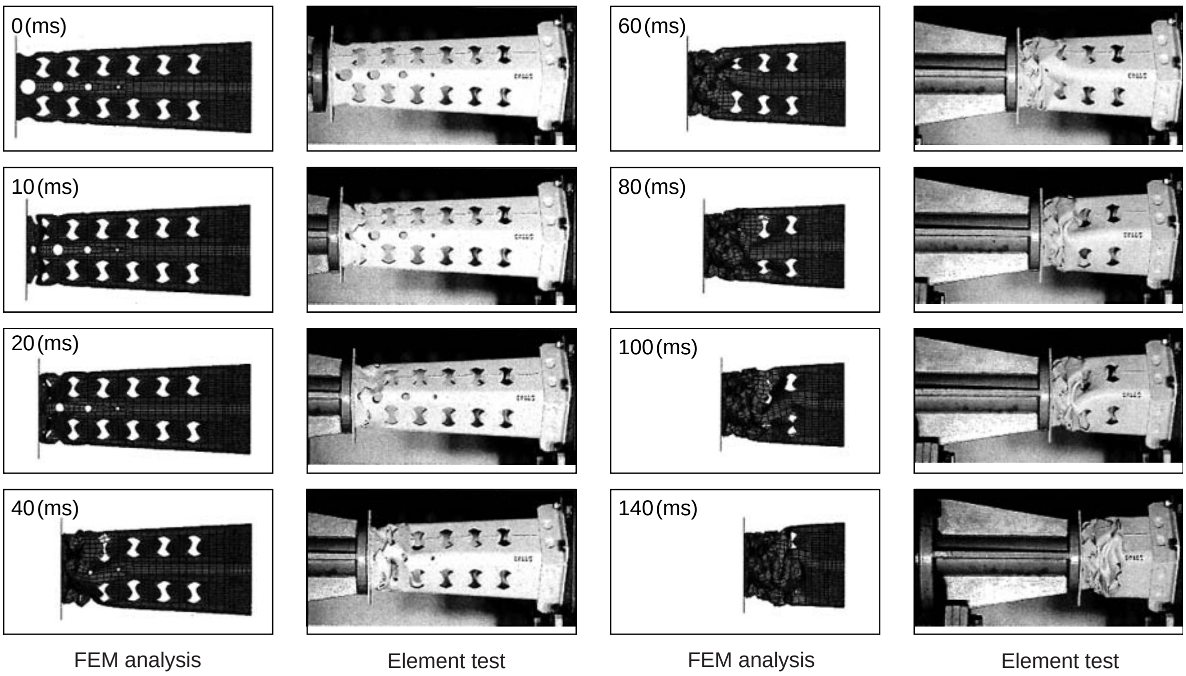

Fig. 6 Deformation process of mechanical fuse

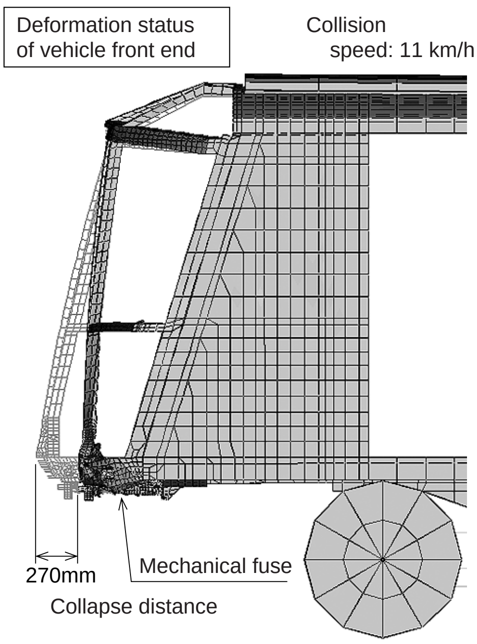

Fig. 7 Analysis result of vehicle collision

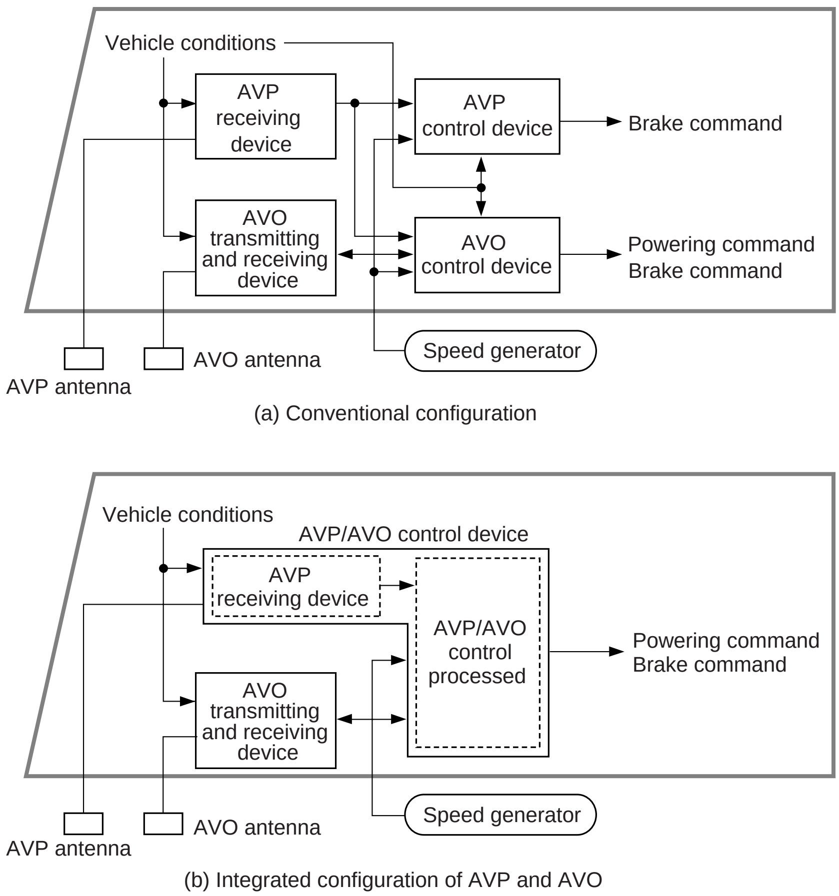

Fig. 8 Configuration of on-board automatic operation control system

lizing CAE analysis and element testing, and favorable results satisfying the design target were obtained. At the same time, by use of the reliable CAE analysis, it was possible to omit expensive actual vehicle testing, the development period was substantially shortened and the cost was reduced.

3.5 Integration of on-board automatic vehicle protection and operation (AVP, AVO)

Signaling and automatic operation system conform to the new transit system in Japan. The on-board devices of which these systems are composed are original devices of APM vehicle for full-automatic driverless operation. These devices were reduced in size and mass in order to be assembled in the limited equipment space of the cabin during the development of the APM with single-car and small body.

The conventional equipment composed of independent devices made by different manufacturers was reviewed, the functions were integrated, and on-board control devices were united and reduced in size and mass. Specifically, safety protection devices such as the AVP receiving device and AVP control device, and the AVO control device necessary for automatic operation are integrated into one unit by reducing their size and mass, and the equipment wiring was simplified.

Fig. 8 (a) is a block diagram of conventional on-board control equipment. As shown in the diagram, the AVP control device and AVO control device have common points in input and output signals such as speed generator input and console input. Making use of these points, the CPU and hardware are shared by the AVP control device and AVO control device, and the AVP receiving device is also incorporated into the same housing. As a result, control from reception of AVP signal to train control and automatic operation can be realized by one device as shown in Fig. 8 (b).

The AVP is a safety protection device for assuring safety of the train, and the AVO is a device for automatic operation. To integrate these two functions whose purpose and nature, are different, the most important point is not to sacrifice the function of the AVP, which is a vital safety protection device. In this respect, the concepts were summarized as follows.

(1) The safety-related software of AVP is isolated from the AVO, and its safety is assured.
(2) The AVO operation is executed in the idle time of the AVP program (while the CPU is not being utilized), and the AVP and AVO are completely independent in function and control logic.
(3) Sharing of variables between AVP and AVO is prohibited. However, the AVO is allowed to refer to the processing results of the AVP.

As a result, the software of the equipment is clearly separate and independent in the functions of AVP and

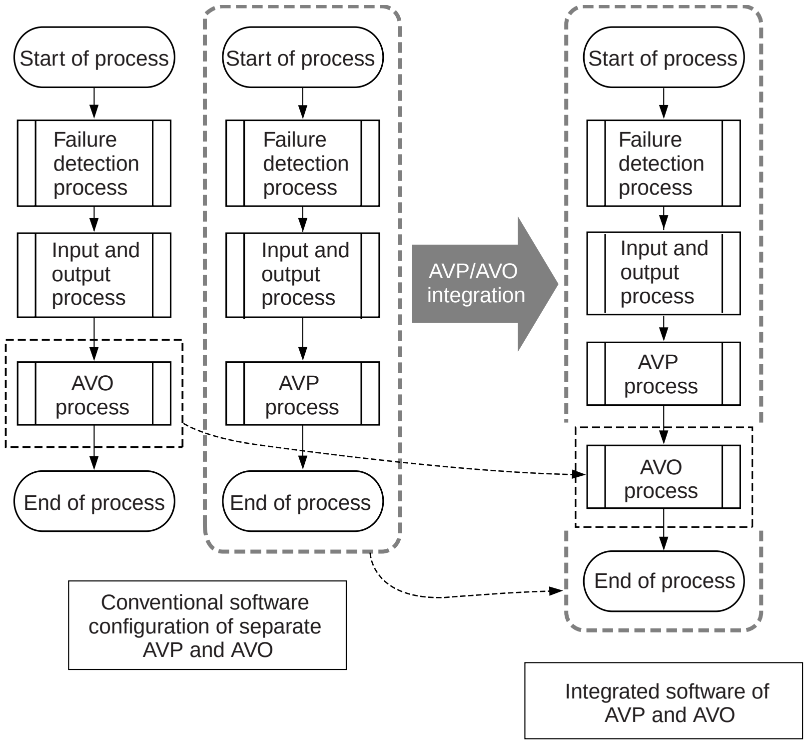

Fig. 9 Concept of software integration of AVP and AVO

AVO, and the role and safety as safety protection device are guaranteed.

The arithmetic processing of the software is a single-thread structure for processing a series of programs sequentially in series conforming to the conventional single constant period interruption. For integration, processing of two functions of AVP and AVO is required, but they are not processed in parallel, and the single-thread structure is employed. This means that after AVP-related processing, AVO-related processing is added programmed to execute them in series. Complication of the program structure is thus avoided. The concept of integration of software is shown in **Fig. 9**.

AVP control function is parallel duplex system, and AVO control function is waiting duplex system, and the reliability is thus enhanced. Although AVP control and AVO control operate in the same CPU system, since the functions are separate for AVP and AVO, troubles are also divided into two types related to the AVP and to the AVO.

Self-diagnosis of hardware (trouble check of CPU, etc.) is a function of the AVP, and if the fault is judged to be a result of checking, it is changed over to another system. Troubles of AVP include common hardware troubles of AVP and AVO, and the AVO is simultaneously judged to be defective.

In the AVO-related functions, only the input and output hardware used in the AVO is checked for trouble. If as a result of checking it is judged to be input and output failure, it is understood as AVO trouble, and all AVO-related outputs are cut off to change over to another system. However, the control of the AVP continues as usual, and with this software and hardware configuration, the AVP-related function is not lost and the control can be continued. This relation is shown in **Fig. 10**.

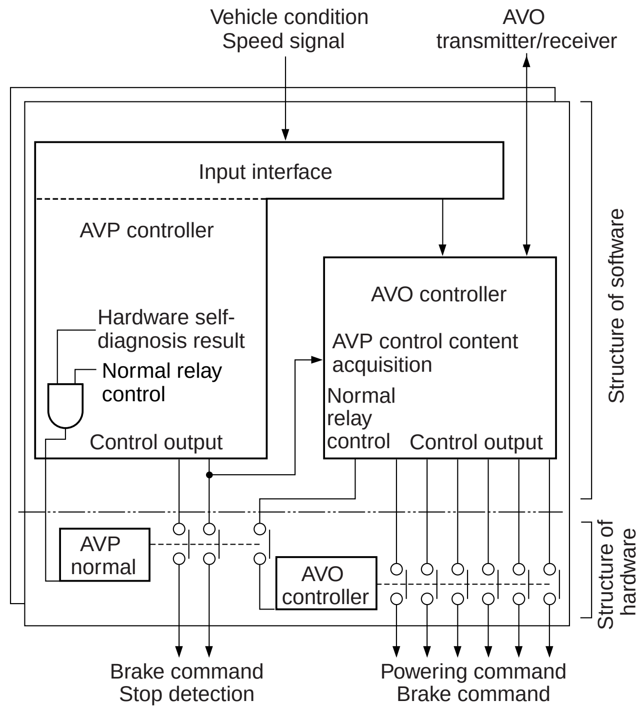

Fig. 10 Integrated function of AVP and AVO

Thus, by integrating the functions, hardware and software of the on-board automatic operation control devices (AVP, AVO), the equipment is reduced in size and mass and the functions are integrated.

3.6 Conforming to overseas specifications and standards

The basic performance and function of full-automatic driverless operation of single-car has been verified and confirmed by a prototype vehicle. Prior to start of mass production for overseas markets, the products must satisfy the individual specification requirements and applicable standards in various overseas projects. The aesthetic design and collision safety are characteristic requirements in overseas markets today, and others are discussed below.

3.6.1 Air conditioning system

Singapore has a tropical climate, and performance and capacity of the air conditioning system are indispensable requirements. The cooling capacity is designed at 32 kW in the vehicle with capacity of 105 passengers in order to keep the cabin in the condition of 26°C DB and 60% RH while taking in fresh air at 0.175 m3/sec in an ambient condition of 34°C DB and 75% RH. As the air conditioning equipment, a thin built-in roof type has been developed to match the vehicle exterior design, and two units are incorporated in the roof at both ends of the vehicle.

To verify the performance of the air conditioning system, in addition to the cooling capacity test on a air conditioner, an environmental test was conducted simulating the environmental conditions of Singapore (temperature, humidity, solar gain, etc.) by using an actual vehicle in the MHI's environmental test laboratory. As the refrigerant, substituent chlorofluorocarbon R407C is used to lessen the global environmental load.

3.6.2 Fireproof performances

Vehicles are required to be fireproof, and the standard in force overseas is strict. In this APM vehicle, the body structure is required to conform to NFPA 130 and its cited standard ASTM. In particular, the floor structure is defined according to the combustion temperature pattern specified on the basis of ASTM E-119, by which the average temperature rise of the floor may not exceed 139°C in 15 minutes as a result of heating and combustion from under the floor. To satisfy this standard, a heat resistant sub-layer of insulating material was provided in the lower side of the underframe structure, and heat conduction to above the floor was suppressed. The fireproof performance was verified by using a full-size floor structure including heat resistant sub-layer and having a combustion test conducted by a third party organization. In addition, interior material and others are also made of materials conforming to the fireproof standard.

3.6.3 Front penetration test

In overseas project, the strength against flying object hitting the front of the vehicle is often required. In this APM vehicle, it was required that an object should not penetrate the front glass or the front structure if hit by the corner of a hollow cubic structure of mass of 0.9 kg and 75 mm on one side specified in BRB/RIA 20 at twice of vehicle speed. To satisfy this requirement, the front

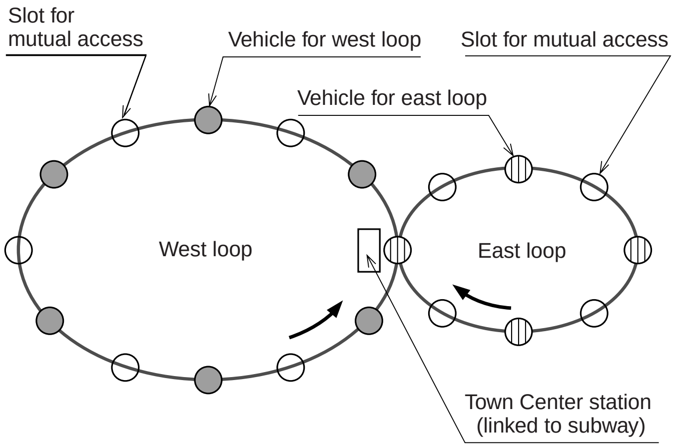

Fig. 11 Concept of synchronous control at convergence point

glass is an aircraft windshield and the other front structures are made of FRP. By verification tests of the materials, the penetration performance was confirmed.

3.6.4 Electromagnetic compatibility

Electronic devices are recently being used for various purposes. The circuits are complicated, and electromagnetic interference between such devices is often reported. Accordingly, there is a mounting demand for electromagnetic compatibility (EMC) - that is, electromagnetic noise should not be emitted from the devices and the devices should not be influenced by incoming electromagnetic noise. This APM system was required to conform to the EN standard. In compliance with the standard, EMC tests were conducted on the individual on-board devices, the whole vehicle, and wayside subsystems. As a result, a satisfactory EMC performance was confirmed.

4. Construction of subsystems

4.1 Operation control system

The operation control system conforms to the new transit system in Japan. In the operation of this APM system, as shown in **Fig. 11**, trains running clockwise and counterclockwise in east and west loops meet at the underground junction station (Town Center). In the existing railway or new transit systems, independent platforms were installed for the east and west loops at the station corresponding to Town Center, and independent line operations were conducted. In this APM system, however, tall guideway structures must be minimized in consideration of the peripheral urban development and other circumstances. Accordingly, independent platforms were not constructed at Town Center station, and the operation management system was designed to allow trains of the east and west loops to use a common platform.

For such operation, the operation intervals on the basis of the transport capacity defined in the east and west loops must be synchronized at the line convergence point. To meet this need, the concept of synchronous control shown in Fig. 11 is employed. In this synchronous control, the train is placed in a position called a slot at the minimum operation interval specified by the customer, and this is coordinated with the middle slot of the opposite side line. In the converging point of the Town Center entry side, block division and signal indication assignment for increasing the operation density between the convergence point and Town Center were implemented in order to control operation at half of the minimum operation interval. Furthermore, to prevent traffic congestion in this section, a departure reduction function was incorporated to adjust the train departure timing at the station before the convergence point using a station control device.

4.2 Electric power distribution system

The electric power distribution system is designed to receive three-phase 50 Hz electric power of 22 kV, at a receiving substation from a host substation, and to distribute the 22 kV power directly to each station. At each station, the 22 kV is stepped down to 400/230 VAC by a local transformer, and distributed to the facilities of the station as necessary. A feeding substation is installed at the vehicle center, the east loop and the west loop. Each feeding substation includes a rectifier and an inverter, and 750 VDC is fed to the vehicle. Usually, the power is supplied to the depot, the east loop and the west loop from each feeding substation, but if one substation fails, by closing the switch provided at the convergence point of the east loop and west loop, power can be supplied from the other substations.

4.3 Guideway and guideway facilities

4.3.1 Guideway geometric design

This APM system is installed in a suburban new town district, and includes loop line formation and cloverleaf. A complicated guideway geometric design, including alignment and profile, was required. From the stage of town planning by construction consultants, original guideway geometric plans and corrective ideas were proposed by simulation, and comfortable ride quality was realized by limiting speeds due to guideway restrictions. The procedure is shown in **Fig. 12**.

(1) Making provisional outline of guideway geometric pattern (proposal by construction consultants).
(2) Evaluation of outline of guideway geometric pattern by running simulation in consideration of operational criteria and vehicle characteristics.
(3) Evaluation of outline of guideway geometry, extraction of alignment and profile elements such as restraint conditions from run-curve, and change of alignment and profile objects to be studied.
(4) Re-evaluation of outline of guideway geometry by further simulation.
(5) Determination of outline of guideway geometric pattern when evaluated favorably.

These five items were repeatedly studied for each station and the outline of geometric pattern was optimized.

4.3.2 Guideway structure

Guide rails are installed on both sides of the guideway to guide the vehicle from both sides. At equal intervals, guide rails of H-section steel are installed.

The power rail is installed on one side of the guideway, and 750 VDC is supplied to the vehicle. The power rail is held at equal intervals together with the guide rails by means of common brackets. The conductor is aluminum, and stainless steel is used on the sliding surface as a wear-resistant material.

A total of 37 switches are installed, 16 on the main lines and 21 in the depot, and all are remote-controlled from the operation control center room.

To indicate the turning direction of the switches for moving the working vehicles at the time of maintenance, a simplified lighting system (line side signal) has been developed. The status display of the signaling machine is indicated by stop, straight ahead, or left (right) by lighting up one signaling machine. The signal is realized by high luminance LED featuring long life, breakage resistance and easy recognition night and day. Further, since the contact point is shared, it is synchronized with the change of the switch by a signal from the operation control center room.

4.4 Maintenance equipment

The depot is adjacent to the Seng Kang Line, and is located on the second floor of the depot of the subway system. The total area is about 3.5 ha, including 21 switches, 8 buffers, 6 vehicle inspection lines, maintenance space, two-story main building with operation control center room, automatic vehicle washing facility, maintenance garage, departure inspection track, stabling yard, power receiving and transforming facilities, and test track for running test after overhaul.

4.5 RAMS

For export of the transportaion system, prior evaluation of reliability and safety of the system is a technical requirement. In this APM system, analysis of RAMS was introduced and executed for evaluation of the Reliabil-

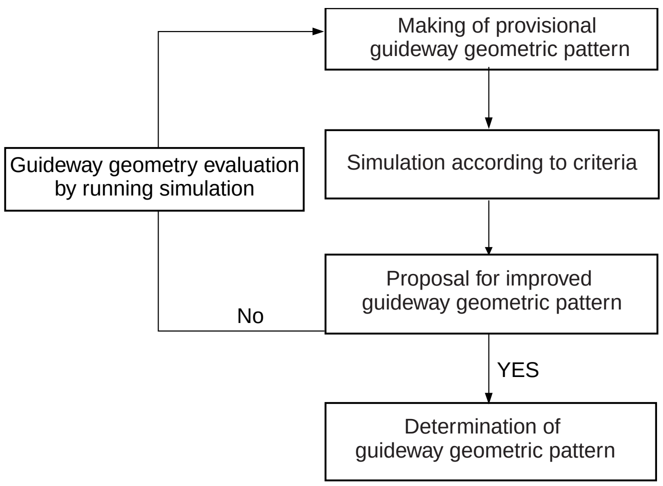

Fig. 12 Optimization routine of guideway geometric design

ity, Availability, Maintainability, and Safety. This RAMS is divided into RAM and S.

In the reliability analysis, using the analytical technique of failure mode effect & criticality analysis (FMECA), the mean time between failures (MTBF) of the entire system was calculated from the MTBF of each line replaceable unit (LRU).

In the maintainability analysis, using the analytical techniques of preventive maintenance analysis (PMA) and corrective maintenance analysis (CMA), the mean time to repair (MTTR) of the entire system was calculated from the MTTR of each LRU.

In the availability analysis, the availability was calculated from the obtained MTBF and MTTR of the entire system. Availability is expressed by MTBF/(MTBF+MTTR). It was confirmed that the result satisfies the required values of availability by 99.00% in vehicles, 99.98% in signaling system, and 99.99% in distribution system.

Safety was analyzed on the basis of the standards of MIL-STD-882C and DEF-STAN-0056.

First, possible hazards occurring in the system were listed. Next, the frequency of incidence of hazards, and degree of damage by hazard were evaluated. The frequency of incidence and degree of damage were classified in six ranks and four ranks, respectively, depending on the severity. The degree of risk is estimated from the ranking of the frequency of incidence and degree of damage.

In each classified risk, safety was analyzed. For safety analysis, the three known techniques are subsystem hazard analysis (SSHA), interface hazard analysis (IHA), and operation & maintenance hazard analysis (OSHA). The SSHA mainly handles hazards caused by trouble of device or unit. The IHA analyzes hazards caused by trouble or defects of interface between subsystems. The OSHA deals with hazards occurring during operation or maintenance control.

By using such procedures and analysis techniques, about 1 400 items of hazard were analyzed by SSHA, about 800 items by IHA, and about 700 items by OSHA. As for high-risk hazards discovered in the process of analysis, proper measures were taken and the risk was lowered. As a result, the hazard risk of the entire system was reduced, and it was confirmed to be free from inconvenience in operation as a transportation system.

5. Conclusion

The Seng Kang Line of APM system for Singapore's LTA started revenue service in January 2003. An outline of the APM vehicles and subsystems supporting them is presented in this paper. MHI hopes that this system will be accepted widely by Singapore people, together with its nickname Crystal Mover, and that it will achieve the specified target as an urban transportation system.

MHI express its deepest gratitude for the help and advice it received in the completion of this APM system.

MACHINERY HEADQUARTERS


Hiroyuki Mochidome


Masahisa Masukawa


Yasuyuki Suzuki


Makoto Kashiwa

NAGASAKI SHIPYARD & MACHINERY WORKS


Shinichi Sadamitsu

HIROSHIMA RESEARCH & DEVELOPMENT CENTER


Hiroyuki Kouno