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ELECTRIC EQUIPMENT OF THE SILENT SAFETY TRAM FOR THE SAPPORO TRAFFIC BUREAU

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I. INTRODUCTION

The Sapporo Traffic Bureau has started to complete the arrangements for a metropolitan traffic network and they plan to construct a high speed tram running from east to west and south to north. The first stage is the south/north line and since 12.7 km of this line from Makomanai to Kita 24-jo is to be opened by the end of 1971, construction is now proceeding. This tram takes the form of a subway in the city center and an elevated tramway in the suburbs. In order to prevent freezing due to the accumulation of heavy snow in the winter months, the entire elevated line is encased in a shelter used for the first time in such tram lines.

In order to prevent a public hazard in the city due to noise and in order to provide safety for the passengers, a new guide rail system using rubber tires has been developed for the trams. The first unit has been undergoing trial operation on a part of the completed track since October, 1970. During January and February, 1971, performance tests were conducted on this tram and it was confirmed that the tram meets the requirements.

Fuji Electric provided the electric equipment and the puncture detection device for this tram line and is currently mass producing this equipment. An outline of the electric equipment will be given in this article.

II. PRINCIPAL RATINGS

The tram consists of an articulated cars with rubber tires with either two units (MC_1 and MC_2) or with 4 units (MC_1, M_3, M_4 and MC_2). The conrol equipment is for two units. In the future, 8 unit operation is planned. The principal ratings are shown in *Table 1*.

Table 1 **Primcipal rating of silent safety tram**

Passenger capacity	90 persons (40 seats, 50 standing)
Interia area	31.99 m^2
Max. dimension	L 13,800 mm B 3,470mm H 3,705mm
Empty weight	16.5 t
Brake	Dynamic brake and electropneumatic brake
Main motor	90 kW×2/car 375 V DC series wound self-ventilated type with interpole
Gear ratio	10.153
Diameter	Pilot wheel 942 mm Drive wheel 1,080 mm Guide wheel 731 mm
Control device	Automatic indirect control with cam motor by load compensation
One-hour rating	Tractive effort 3,590 kg (per unit) 31.3 km/h
Max. speed	70 km/h
Acceleration	4 km/h/s
Retardation	4 km/h/s

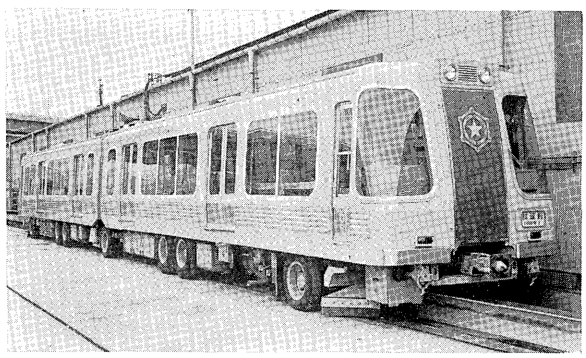


Fig. 1 Silent safety tram for Sapporo Traffic Bureau

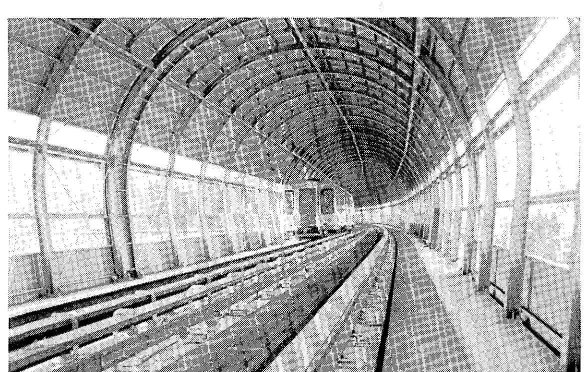
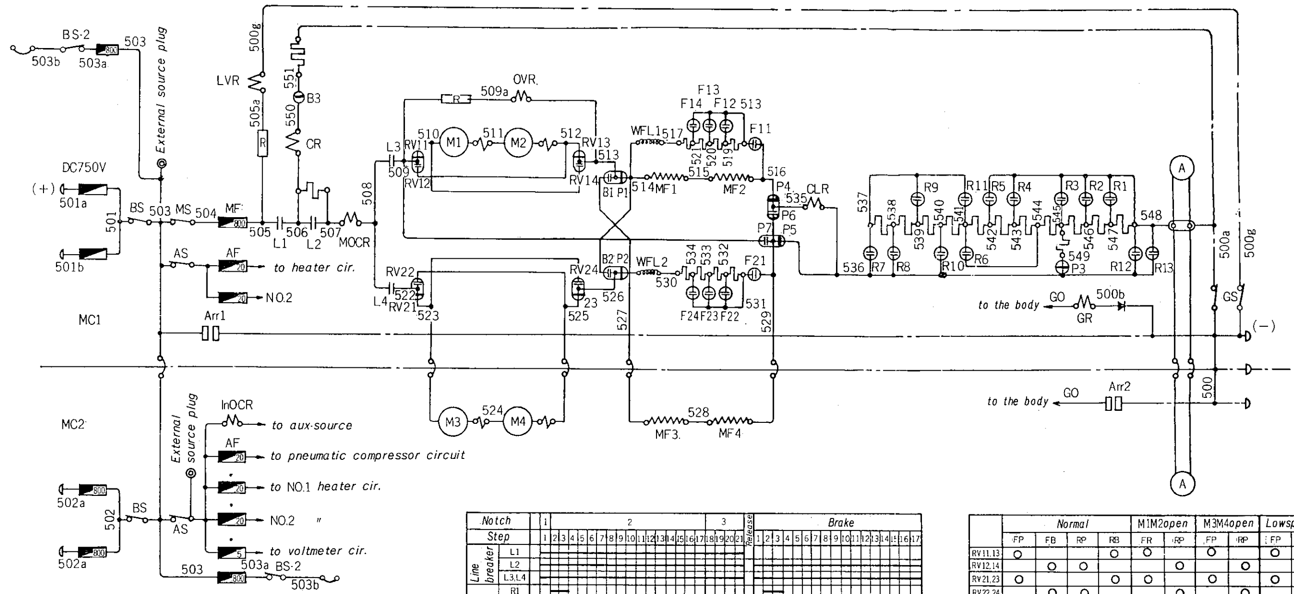


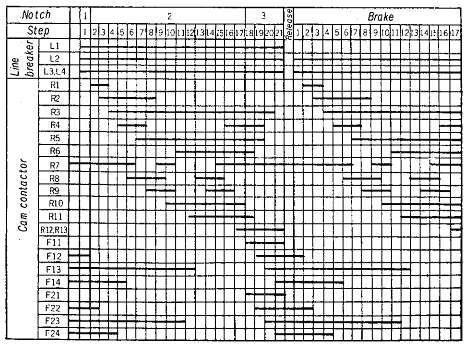
Fig. 2 Rail track of elevated line

III. CONTROL EQUIPMENT

This is a special tram of a completely new type and there are various limitations concerning the devices placed on the train. The following points must be noted concerning the electric equipment.



Symbol	Name	Symbol	Name
A	DC ammeter	L1~4	Line breaker
AF	Fuse (high voltage aux. circuit)	LVR	Low voltage relay
Arr 1,2	Arrester	M1~4	Traction motor
AS	Disconnector (high voltage aux. cir.)	MF1~4	Field coil
B1~3	Cam contactor (B raking)	MOCR	Over corrent relay
BS	Main discconnector	MS	Disconnector (main cir.)
CLR	Current limit relay	OVR	Overvoltage relay
CR	Current relay	P1~6	Cam contactor (powering)
$F^{11\sim14}_{21\sim24}$	Cam contactor (fieldcontrol)	R1~13	Com contactor (resistant control)
GR	Ground rely	$RV^{11\sim14}_{21\sim24}$	Cam contactorl (reverse)
InOCR	Overcurrent relay	WFL	Inductive shunt coil



	Normal				M1M2open		M3M4open		Lowspeed	
	FP	FB	RP	RB	FR	RP	FP	RP	FP	RP
RV11,13	O			O	O		O		O	
RV12,14		O	O			O		O		O
RV21,23	O			O	O		O		O	
RV22,24		O	O			O		O		O
P1	O		O		O	O	O	O	O	O
P2	O		O		O	O	O	O	O	O
P3	O		O							
P4	O	O	O	O			O	O	O	O
P5	O	O	O	O						
P6					O	O				
B1		O		O						
B2		O		O						
B3		O		O						
B7									O	O

Fig. 3 **Main circuit diagram**

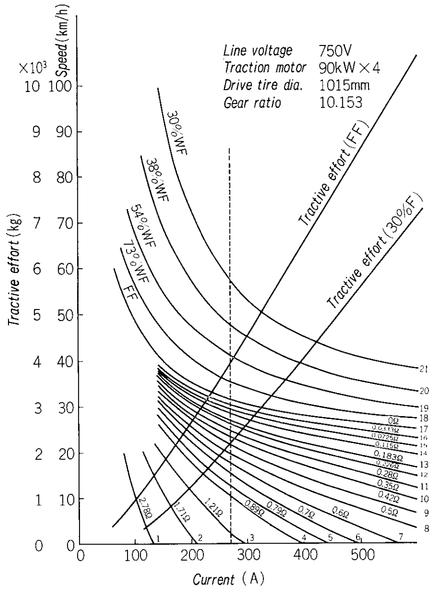


Fig. 4 **Notching curve (powering)**

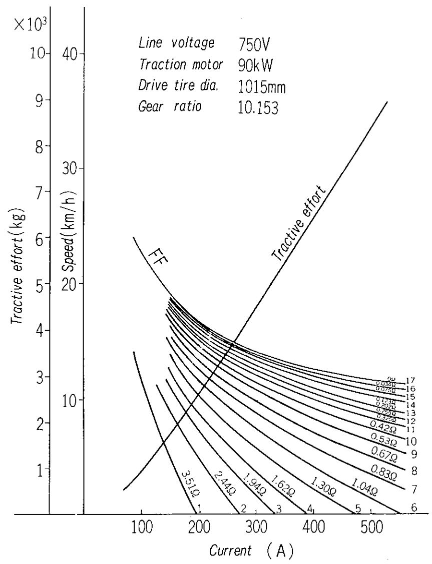


Fig. 5 **Notching curve (powering at low speed)**

1) It is essential that the weight of the units be small because of the rubber tires. The electric equipment also had to be very light weight.
2) There are many limitations concerning the space under the floor in comparison with normal trams because of the guide rail and guide wheel, etc. and therefore the space must be a compact as possible.
3) This is a silent train and it had to made so that noise of the collector and traction motor, etc. were as small as possible.
4) Since the train is used in a cold region, it was necessary to be sure that the equipment could withstand the cold by providing heater in required parts, etc. in order to guarantee performance during low temperatures.

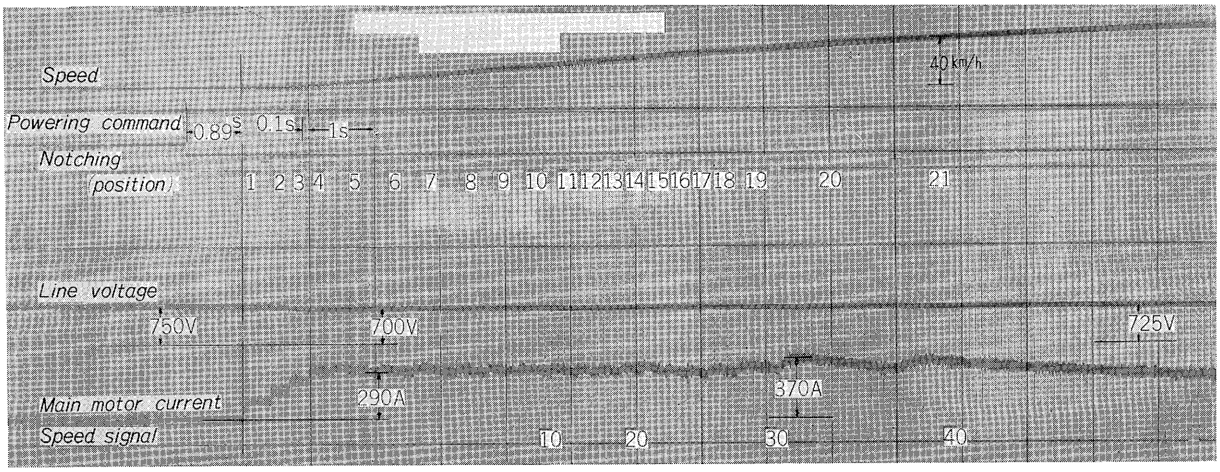


Fig. 6 Oscillogram of starting

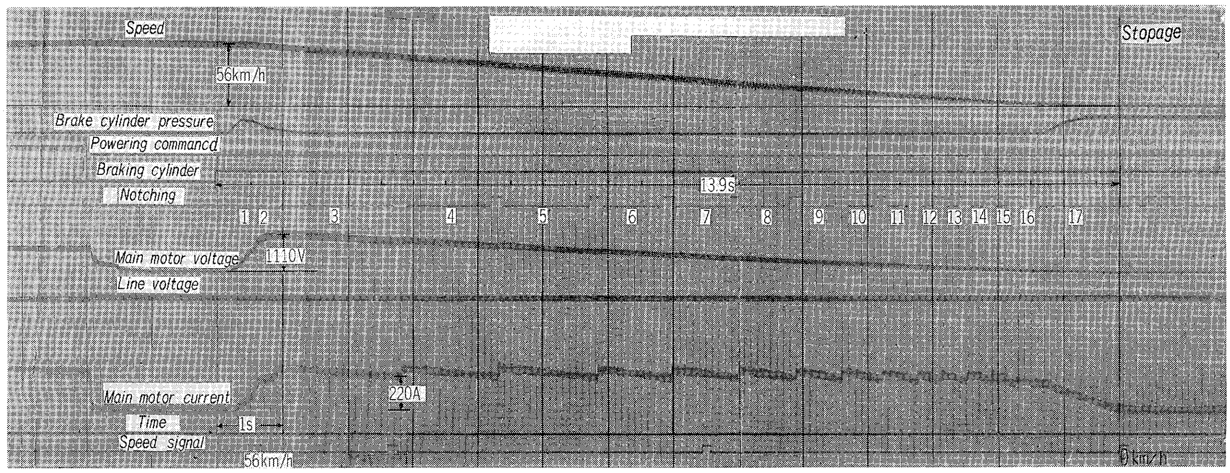


Fig. 7 Oscillogram of dynamic brake

5) Part of the line is underground and it was necessary to consider fire prevention measures because of the rubber tire system, etc.
6) Since under-floor operation is impossible due to the third rail, all operations had to be performed on the floor of the units.

Fig. 3 is the main circuit diagram. There are four main motors connected in a 2S-2P configuration which perform resistance control and field control. Low speed control by the 4S connection in which the train can be operated at less than the limit speed of 15 km/h even on maximum grades of 43% is also possible. *Figs. 4* to *6* show the notching curves and oscillograms from actual tests. Since the notching is correct through the resistance and field control and there is an appropriate idle notch, smooth starting is performed even at high accelerations.

The brake system employs both dynamic and pneumatic braking. The dynamic brake is operated by the cross field of the 2S-2P main motors through operation of the brake control device. The notching curve of the dynamic brake and an actual test oscillogram are shown in *Figs. 7* and *8* respectively. In order to establish dynamic braking rapidly, con-

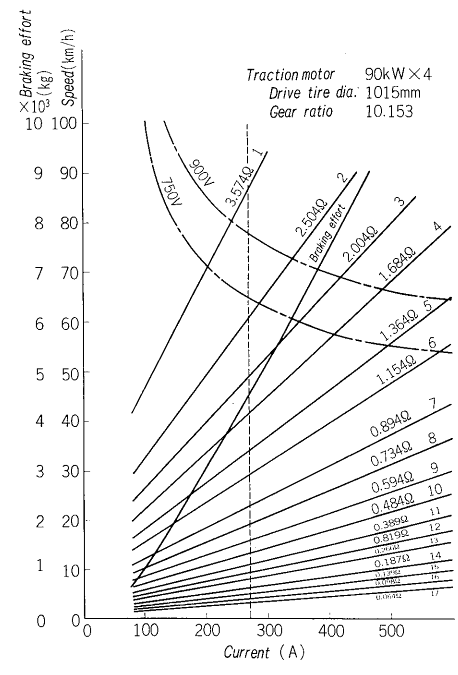


Fig. 8 Notching curve (dynamic brake)

version to the brake circuit is accomplished by coasting and there is little unnecessary notching at the ordinary initial braking speed of 50 km/h. Therefore the dynamic brake is established in 0.5 seconds. Notching is also excellent and dynamic braking is effective even at low speeds.

1. Main Motors

The main motors are attached to the under-frame of the tram cars and there is one drive shaft for each motor. The motor power is transferred from the main motor to the driving axle via the universal joint, splined shaft, reduction gear and differential gear.

The armature core is a lamination of silicon steel plates and the construction is water-proof because the commutator spider and the armature core cramp are in the form of one unit. The coil employs a right angle copper strip with highly heat resistant " nomex tape " insulation and compact size and high performance of the motor are achieved by impregnating solventless epoxy resin varnish.

The commutators are of the arch bound type and each connection part is made water and dust-proof by means of silicon rubber packing. The commutator pieces employ silver-contained copper, the riser is of the solid type and the armature coil connection is by tungsten inert gas welding. A suitable design has been used for the insulation system.

The magnetic frame of the stator is circular with steel plate welded construction. The main pole core

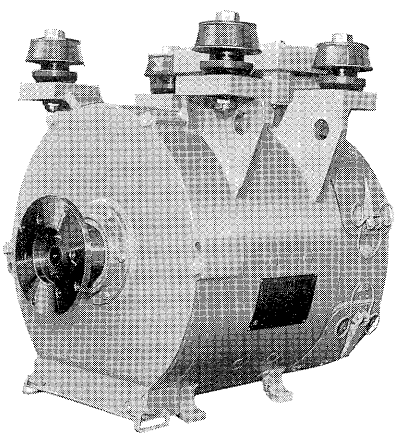


Fig. 9 Main motor

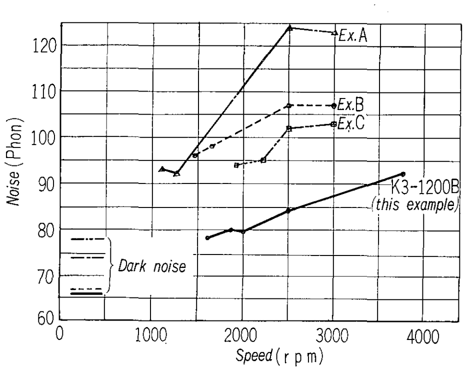


Fig. 10 Noise of main motor

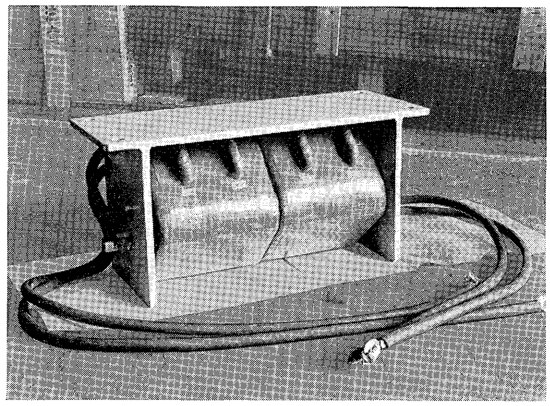


Fig. 11 Inductive shunt coil

is a lamination of steel plates and the inter pole core is in the form of a block. The main pole coil is flat wound in two levels and the inter pole coil is wound edgewise with collected mica tape and glass tape insulation. The core is held in place by solventless epoxy resin varnish. Connections between the coils are soldered using a bar.

With such new techniques, the motor can be smaller and lighter and the reliability is improved. In order to extend the maintenance interval to save labor, shield bearings are used for both the ball bearing on the commutator side and for the roller bearing on the opposite side to the commutator. The brush holder is the Fuji Electric constant-pressure type holder with the standard maintenance free system of the Japanese National Railways. With this holder, long divided brushes are used.

In order to prevent noise on this silent safety tram, several measures were taken including the use of a low noise fan for self-cooling, a noise reduction design for the air outlets and a large increase in the length of the air gap of both end of the main pole core. As can be seen from *Fig. 10*, the noise is much less than in any ordinary tram.

The main motor is used in such a way that the weakest field factor is as low as 30% with the inductive shunt. In this shunt, the shunt resistor and the inductive shunt coil are included. *Fig. 11* shows the inductive shunt coil, suspended beneath the floor of the tram. This is open core type equipment and the core is made of a lamination of thin steel plates. The coil employs flat type aluminum strip and is designed to be compact and light weight. Insulation is by collected mica and glass tape and the coil is held in position by epoxy resin. There are two such coils, one for each of the two main motors.

2. Main Controller

This device powers the 4 main motors of the two trams and controls the dynamic brake. The controller consists of two cam shafts. The control cam shaft is of the one direction operation type and has a total of 21 steps, 17 resistance control steps and 4 field control steps. The resistance control steps

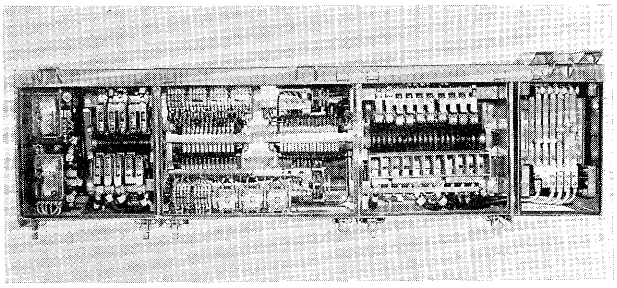
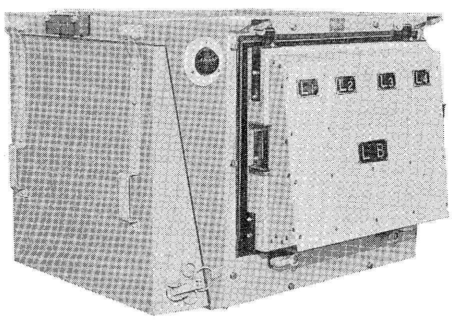


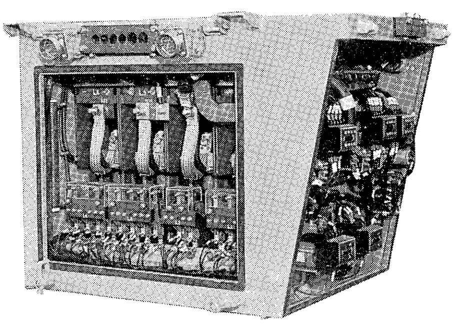
Fig. 12 Main controller

are also used during dynamic braking. The conversion cam shaft is of the reversible operation type and is used for conversion of main circuits such as forward/reverse conversion, powering/brake conversion, switching off of the main motor circuit during accidents and low speed control. This cam shaft is driven via a gear wheel device by a small DC shunt motor. The control cam shaft in particular is started and stopped frequently so that the cam motor is controlled by a contactless relay system. The cam contactor is of the unit type and transfer contact types are used in the conversion cam shaft.

In order to decrease the connection between the apparatus as possible, a shunt resistor for field control is attached on the main controller side. However, as a fire prevention measure, the shunt resistor is placed in a separate box, an air gap is arranged between it and the side of the main controller and the exhaust from the resistor is discharged in the side direction of the tram.



(a) Front view



(b) Rear view

Fig. 13 Line breaker

3. Line Breaker

This breaker switches the powering and braking. circuit. It consists of 4 unit switches and protective relays for overcurrent, overvoltage, grounding and low voltages.

The unit switches are of the double contact type which separate the main contactor and the arcing contactor. This type simplifies maintenance. The protective relays are compact with stable performance and reliability. The contacts and electromagnet are common to all the relays and a reset mechanism or a scale adjuster can be attached depending on the application. In the air pipe of the unit switch operating cylinder, there is a tape heater to prevent the freezing of water drops during the winter.

4. Main Resistor

The main resistor consists of 4 naturally ventilated boxes, arranged in a series under the tram floor. Since both ends of these resistors are near the rubber tires, side plates are used. These plates prevent any heat effects on the tires and also act as mud guards. The resistor consists of iron-chrome resistors arranged in the form of a belt. Each box has resistors stacked on support insulators with 7 to 8 stages. These insulators are attached at both ends to the frame with bolts.

IV. CURRENT COLLECTOR

The power supply system is of the non-grounded type. For the positive rail, i.e. the third rail, there is a 50 kg conducting rail and for the negative, rail, which is also used as the guide rail, I-shaped steel is used. The sliding system of both the negative and positive current collectors is on the surface of the rail and the link system is a parallel type such that the current collector sliding plate is always parallel to the rail surface because of the large amount of up/down movement of the truck which arises by use of the rubber tires.

The contact pressure of the current collector is almost constant throughout the operating range and

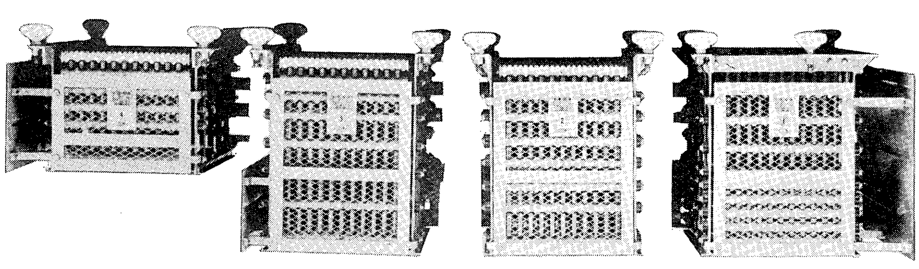


Fig. 14 Main resistor

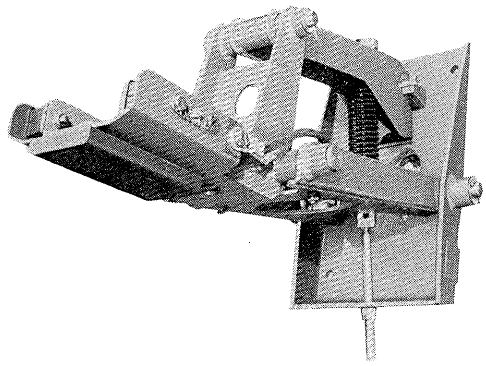


Fig. 15 Current collector (plus side)

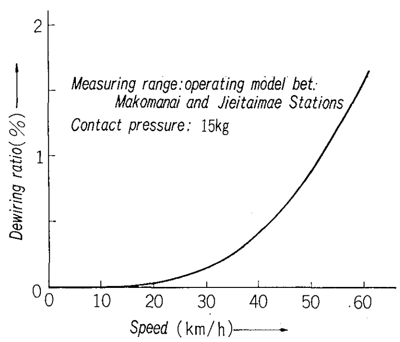


Fig. 16 Dewiring ratio of current collector

the pressure is also adjustable. In order to increase the performance of the current collector, the weight of each part is minimized as much as possible and the movable parts are suspended on anti-vibration rubber with up/down elasticity so that the weight of these movable parts can also be very low. *Fig. 16* shows the dewiring ratio of the positive current collector, and as is evident from this drawing, very good current collection effects are achieved.

Fig. 17 shows an oscillogram of dewiring of the current collector. The performance of the current collector is also improved by the use of a vibration-proof rubber for attachment. This rubber also prevents damage due to impacts from the sliding parts and is effective in decreasing the noise.

V. AUXILIARY POWER SOURCE

A thyristor inverter is employed to supply low voltage power for the lighting, control and other loads on the tram. This inverter is of the static contactless type and has the following features:

(1) Parts subjected to wear are few and maintenance is almost unnecessary.

(2) Since forced ventillation like with the motor-generator is not used, completely enclosed construction is possible and there is little noise.

(3) Conversion efficiency is high.

This equipment has the following specifications:

Type: Single-phase bridge-type thyristor-inverter (stable voltage control by pulse width control)

Capacity: 9 kVA

Input voltage: DC 750 V (variation range: 500-825 V)

Output voltage	capacity	main load
AC100 V (sine wave)	2 kVA	lighting
AC100 V (rect. wave)	4 kVA	heater
DC100 V	3 kW	control power supply

Output frequency: 50 Hz

The construction is as shown in *Fig. 19*. The circuit system is a single phase bridge with a potential transformer for feedback. The current energy is fed back to the power source and the efficiency is good. In order to make the equipment compact, the heater circuit supplies rectangular waves directly and filters can be spared. The sine wave voltage is such that the value remains constant even when there is a change in the high voltage power supply. Among the 4 arms of the bridge, 2 arms have a variable phase and by shifting the thyristor conducting time in respect to the set phase arms, the constant voltage can be maintained. Even when there are short current stoppages for transition of the switch points or dewiring of the current collector due to the special characteristics of the tram, the circuits are not interrupted and dewiring detection is carried out in such a way that it is handled inside the inverter. The DC output distributes the control load and charges the battery with a floating charge.

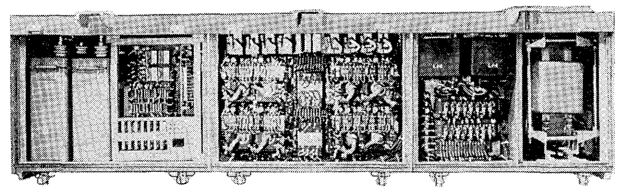


Fig. 18 Thyristor inverter

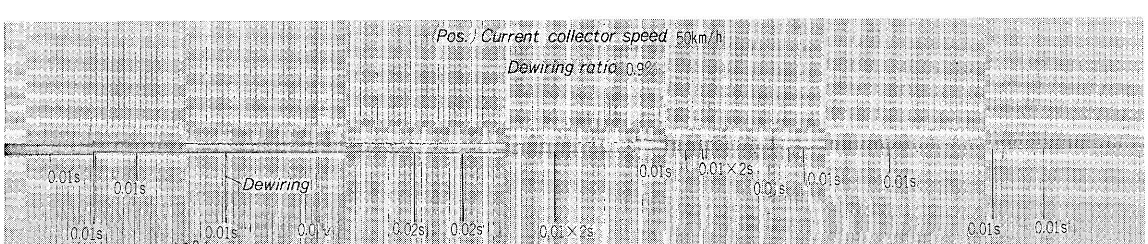


Fig. 17 Oscillogram of current collector dewiring

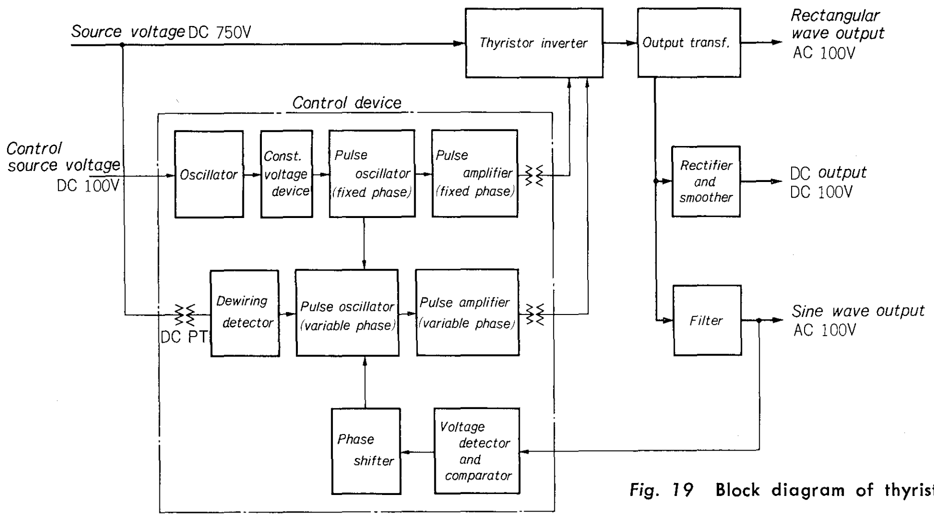


Fig. 19 **Block diagram of thyristor inverter**

The battery has a capacity to run the tram for 30 minutes (12 km) when there is an accident in the auxiliary power source and to provide two hours of lighting with emergency lamps during a power failure. The battery is of the 22AH alkali sintered type. The DC power source converts to DC from rectangular waves by means of a rectifier which uses a set voltage transformer. By limiting the size of the charging current, overloads in the inverter are prevented.

The tram inverter operates under such severe requirements as large input voltages changes, frequent effects on the control power source by surge voltages, ability to resist vibrations, compactness and light weight, etc. However, this equipment has been designed in such a way that sufficient stability can be maintained.

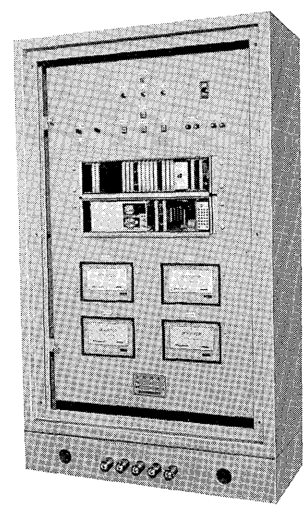


Fig. 20 **Control unit of puncture**

VI. PUNCTURE DETECTOR

Since this tram employs rubber tires, punctures can occur but since there are several tires for each unit, continuous operation without any stoppages is possible even when a puncture occurs in one of the tires. However, when a puncture occurs, it is necessary to detect it as promptly as possible to prevent the accident from spreading to other tires.

Tire puncture detectors usually detect the pressure inside the tire. This is converted into an electrical signal and displayed in the tram. However, in such cases, it is necessary to provide individual detectors for each tire and in this tram, it is necessary to provide for 7 axles (2 front axles, 4 drive axles and 1 connection axle) with 4 tires each for a total of 28 tires. This presents difficulties both in terms of maintenance and economy. Fortunately, since the area which the tires pass over in this tram is almost constant because of the guide rail system, a ground type detection system has been developed for the puncture detector. This system discriminates the load ratios between the wheels by detecting the tire load when the tram passes over a load detector located on the ground. If a puncture is detected, the indicator lamp placed avove the ground lights to warm the driver and an indication is also given

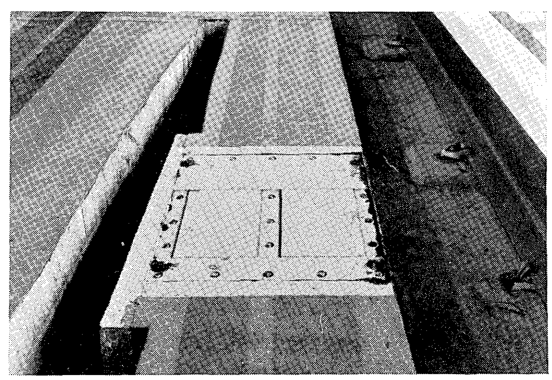


Fig. 21 **Transducer of puncture detector**

Table 2 **Load of type**

(kg)

	Front wheel	Drive wheel	Articulated car wheel
Empty load	1095	1350	656
Full load	1880	2830	1075

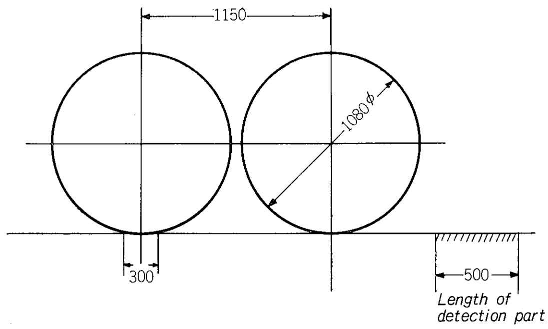


Fig. 22 **Arrangement of drive wheel**

on the operation display panel in the central instruction location.

This is the first example of such equipment and there were many points which had to be considered during the design. The main points are as follows:

1) Differences in tire loads

Table 2 shows the differences in loads for each tire. There are large changes in the tire load due to fluctuation in the load. Therefore, the load detector must have linear characteristics over a wide range and the puncture detector must detect load ratios.

2) Differences in tire shape

The tires are divided into front, drive and connection tires and the tire diameters and widths vary. Therefore, the middle of the load detection plate does not always match the middle of the tire. The detector plate is of the hinge type so that even in such cases correct load detection is possible and the detector has a one-point support. Because of thus type of construction, the detection accuracy is not affected even when variations occur in the imbedded panel.

3) Maximum value comparison system

When there are discrepancies in the tram, a change occurs in the signal of the load detector. Even in such cases, there is no problem in the detection since the maximum values are stored and a comparison is made between these maximum values.

4) Nearness of set shaft distances

As can be seen from *Fig. 22*, the distances between the drive wheels is very short and the gap between the tires is about 70 mm. At the time of full load, the tires have a flatness of approximately 300 mm. If there is any abnormality in the front drive tires at this time, preparations must be made to pass to the next drive wheel. The dimensions of the detection plate are limited and since there are cases when the tram speed is 70 km/h, the comparison detection must be made very rapidly. Therefore, the comparison of the detected loads is within the very short period of 1 ms after there is no load for the detection plate

5) Load detector

The load detector employs a highly accurate, enclosed load cell which can be used over long periods. Since the output signal of this load cell is very low, misoperations due to surges, etc. must be prevented.

The main problem in the load detector is that there must be no misoperation of the correct tires even though the trams run under various speeds and various conditions (powering, coasting, braking). In addition, the puncture detector must make correct

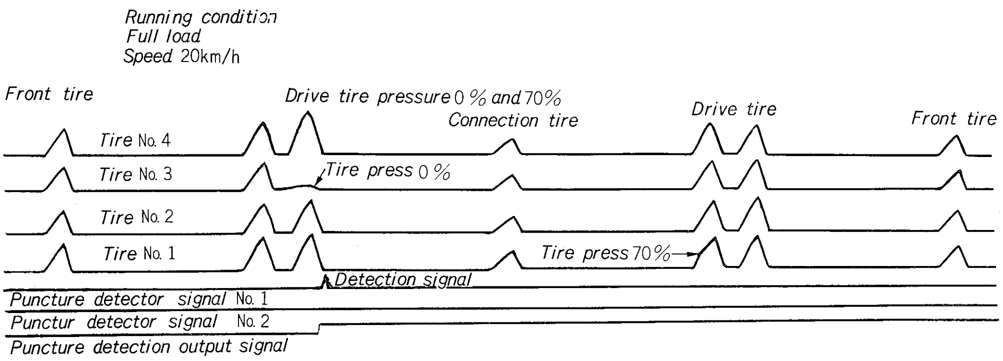


Fig. 23 **Oscillogram of puncture detector**

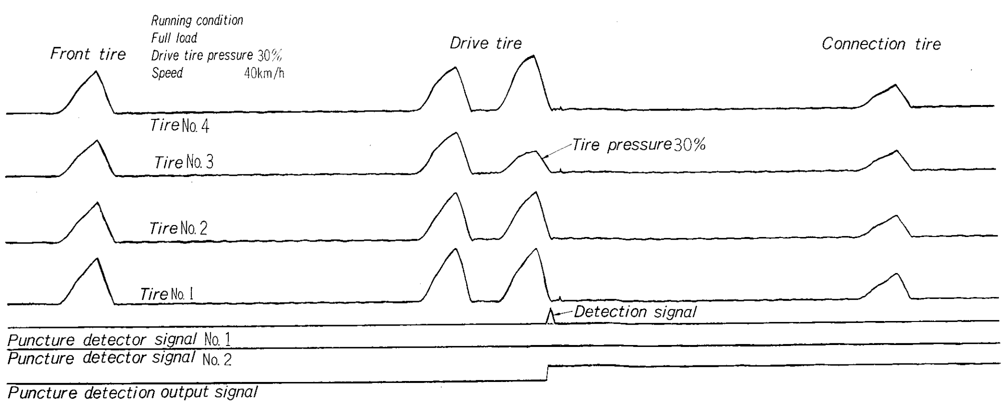


Fig. 24 **Oscillogram of puncture detector**

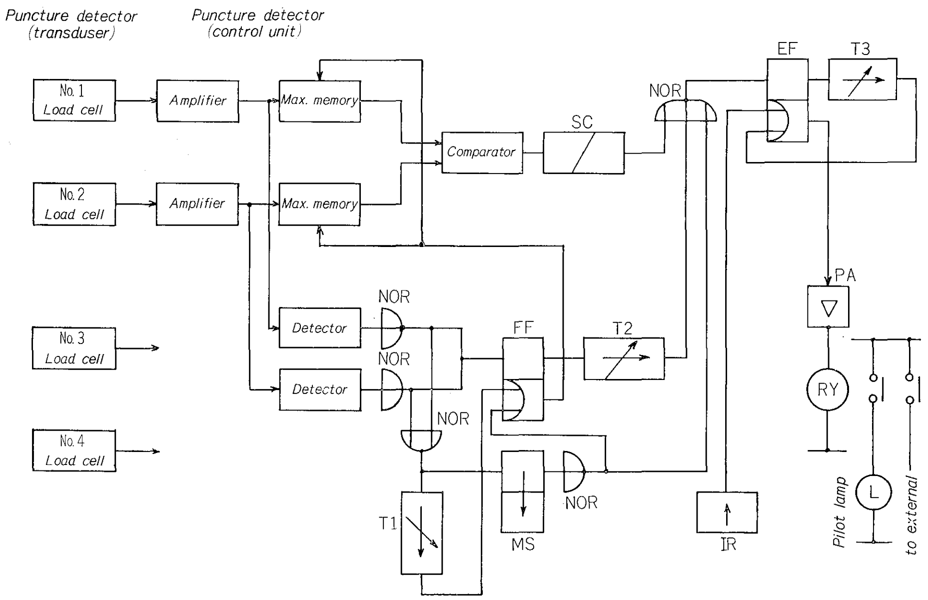


Fig. 25 **Block diagram of puncture detector**

detections and thus the value of the detection ratio K must be selected accordingly.

$$K = \frac{\text{punctured tire load}}{\text{normal tire load}}$$

In the factory tests and the site tests, a considerable amount of data was collected and the effective detection ratio was 0.5 when the tire load is slight on one wheel, the load is simply increased on the other wheel.
Therefore:

$$K = \frac{1-\alpha}{1+\alpha} \text{ where } \alpha = \text{load change portion}$$

Therefore, when $K=0.5$, $\alpha=0.33$.

In other words, it is possible to detect the time when load share is increasing at a rate of approximately 30% in respect to ordinary powering. *Figs. 23* and *24* show examples of cases when the pressure inside the drive wheels is 0%, 70% and 30% of the nominal. In the cases of 0% and 30%, a puncture signal is given but in the case of 70%, the load difference is small ($K=0.8$, $\alpha=0.11$) and there is no detector operation. This type of equipment is highly rational in that it evaluates tire punctures from all points by means of load unbalance due to changes in the tire pressure, differences in the wear of adjacent tires, etc. After it is imbedded in the actual line, it will become active in the near future.

This equipment consists of the ground equipment imbedded in the operating surface of the tram and electrical equipment installed nearby. In the electrical equipment, the output from the load cell is amplified, compared and a detection signal is given to the exterior. The construction of the electrical equipment is shown in *Fig. 25*. The electrical equipment also contains a test switch for evaluation of the performance of the equipment in cases when the tram is not actually operating. By input of the same signal as if a tram were actually passing, it is possible to check the operating conditions.

VII. CONCLUTION

This article has introduced electric equipment for a silent safety tram delivered to the Sapporo Traffic Bureau. This tramway is planned for the winter Olympics in Sapporo in 1972. It is a new type with rubber tires which will probably attract attention both in Japan and abroad. The commercial operation began on December, 15th upon completion of performance test operation and is continued to operate satisfactorily.

Finally the authors wish to thank all of those in the Sapporo Traffic Bureau and the rolling stock divisions of Kawasaki Heavy Industries who aided in the design, manufacture and testing of this electrical equipment.