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**Paper**

# Evaluating the Accuracy of Railway Total Simulator Compared with Actual Measurement Data

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We developed a railway total simulator that can simulate not only each sub system such as a train, signalling system, and power supply system but also train operation and energy usage based on the collaboration of subsystems for all railroads. The purpose of this simulator is to determine the influence of the energy consumption of trains and substations depending on the change in train characteristics, timetables, power supply systems and so on. The targets of calculation for this simulator are the energy consumption of substations and trains restricted by the condition of signalling systems and traffic control systems. We evaluate the simulation accuracy of the proposed simulator for a DC feeding system by using measurements obtained from the Okinawa Urban Monorail. It is confirmed that the simulation results can help predict power behaviour with a sufficient accuracy on railway lines and the average simulation differences were within 6%, namely a 3.6% difference in rolling stock power consumption, 3.9% difference in rolling stock regenerative power, and 3.0% difference in substation power supply. On comparing the calculation results of the proposed simulator with actual measurement data from a general DC power railway system, it is concluded that the simulator and actual results have a sufficiently low difference.

**Keywords:** simulation, actual measurement data

## 1. Introduction

In recent years, awareness of environmental problems has been growing around the world. Although railways are recognized as an energy efficient mode of transportation that consumes less energy per kilometre for each person carried than other systems such as cars and airplanes, there is a need to achieve even greater energy efficiency in response to environment problems. Since the energy used for train operation accounts for approximately 70% of the total energy consumed by these railway systems, reducing the energy consumption of train operation plays an important role in encouraging energy efficiency [(1)].

Railway systems are large and complex. A railway system consists of the rolling stock that carries passengers, signalling systems that ensure safety, traffic management system that ensures smooth train operation, substations that supply electric power, power management system that monitors the substations, stations where passengers get on and off and station buildings.

To analyse the energy used for train operation, we developed Railway Total Simulator which models the elements that affect train behaviour. The targets of modelling are rolling stock, signalling systems, traffic management systems and power supply systems. Power supply systems include substations and power management systems.

When considering energy saving measures for train operation, it is important to analyse how much room there is to improve train operation energy. Moreover, it is also important to perform a quantitative comparison before and after introducing energy saving measures. Simulation technology is essential for calculating quantitative values. The accuracy of the technology is important for measuring the impact of predicted values when introducing energy saving measures. Therefore, we need a highly accurate railway simulator. In this paper, we evaluate the simulation accuracy of Railway Total Simulator for a DC feeding system by using measurements obtained on the Okinawa Urban Monorail.

## 2. Overview of Railway Total Simulator

We started developing simulators for DC feeding systems in the 1970's and developed Railway Total Simulator in 2010 [(4)]. Railway Total Simulator can simulate not only each sub system such as train, signalling system, and power supply system but also train operation and energy usage on the basis of collaboration of subsystems for all railroads.

Railway simulators that calculate the energy consumption of trains and substations have been developed and written about in various documents [(2)–(7)]. However, there are few reports in which accuracy was verified [(3)–(5)]. We developed our simulator because we need a highly accurate railway simulator as indicated above. Our simulator models physical models such as trains and substations in detail by using multiple parameters. For example, a rolling stock model is modelled by using multiple parameters such as tare weight, passenger weight, length, running resistance, inverter efficiency, motor

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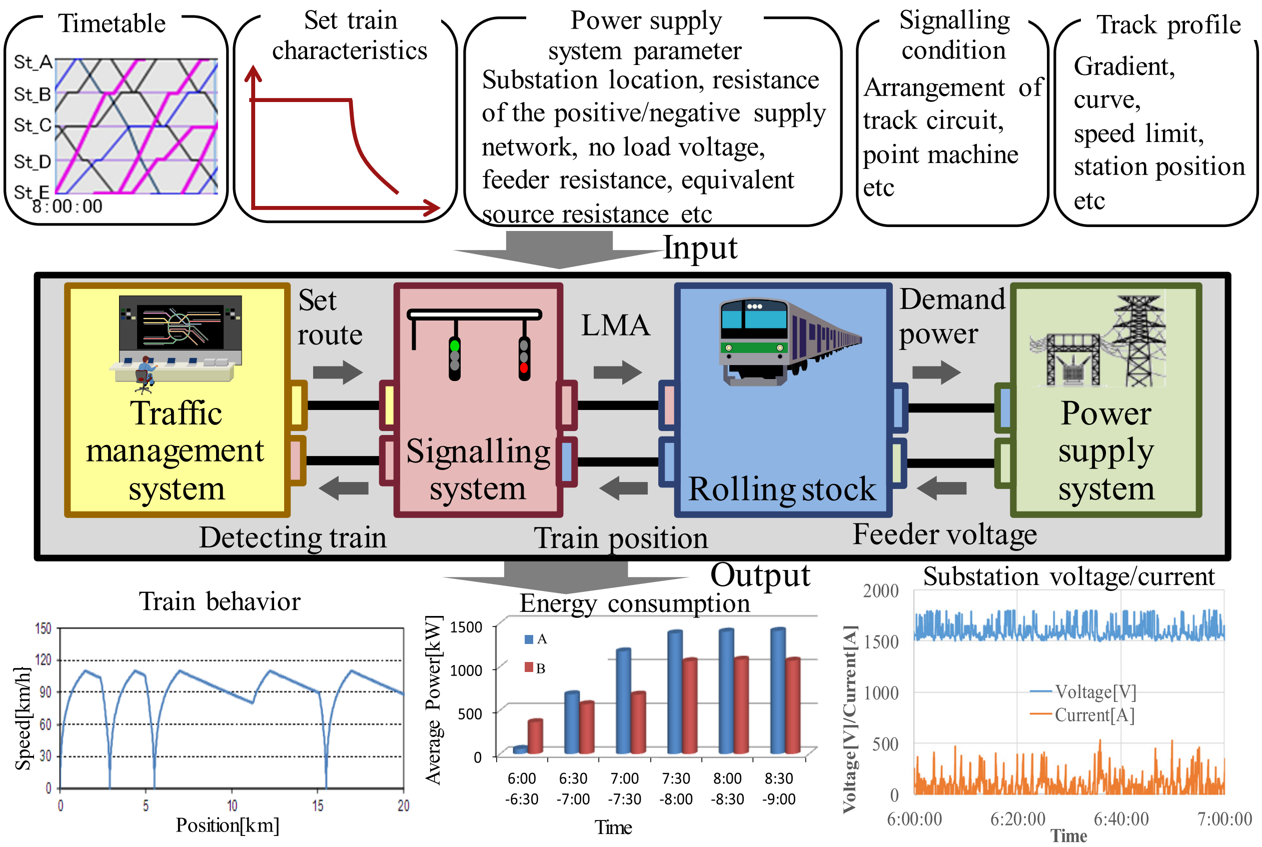



Fig. 1. Overview of railway total simulator

efficiency, gear efficiency, tractive force, electric-brake force, deceleration and auxiliary power supply. The model also has a controller model that changes the tractive force and electric brake force according to the feeder voltage. Moreover, on the basis of research results so far, we know that the energy consumption of rolling stock will change significantly due to the difference in running patterns. To accurately calculate the energy consumption of rolling stock, we need the running pattern of a simulation to match with an actually measured running pattern. The electric power characteristics of rolling stock are small in the low-speed region near stopping and departing and are less influential on the total energy consumption. In comparison, they are large in the middle- and high-speed regions and are more influential on the total energy consumption. Therefore, it is essential to accurately model running patterns in the middle- and high-speed regions. We developed a driver model that selects a driver notch so that the speed is close to the actually measured running pattern. Specifically, for all driver notches, it compares the speed when each notch is applied and the measured speed at that position and selects the best one.

An overview is shown in Fig. 1. The input conditions are timetables, train characteristics, power supply system parameters, signalling conditions, and track profiles. On the basis of these inputs, the simulator cooperates with four subsystems to predict train operation, signal control, and electric power consumption. We use the simulator to design the specifications of traction equipment and power equipment by estimating the power consumption in a target railway line.

The simulation flow is shown in Fig. 2. The traffic management system model simulates route control and time management for arrivals and departures on the basis of a train's position, timetable, and track profile. Next, we explain the operation of the signalling system. The input data of the system are the arrangement of the track circuit and point machine, which is needed for setting the upper speed limit for each track circuit. The signalling system decides the speed limit of each train from the interval between the position of each train and the limit of movement authority (LMA) where each train can enter, which is determined from the position and behaviour of the preceding train for each train and the open state of the point machine. Therefore, it is possible to calculate the energy consumption of a train and substation under various conditions considering other trains and timetables.

The rolling stock model consist of three models: a driver model, propulsion model, and vehicle movement model. Our simulator decides driver commands on the basis of a running pattern and LMA with the driver model, and it calculates tractive force and demand power on the basis of driver commands, train speed, and feeder voltage with the propulsion model. The power supply model makes circuit equations using Kirchhoff's law and Ohm's law on the basis of the train's position, electrical network, such as a substation's location, and power supply system parameters. Moreover, it calculates convergence loops until the feeder voltage and demand power are displaced. Finally, it updates the train's position and speed with the vehicle movement model using equation of motion. The target of calculation with this simulator is the energy consumption of substations and trains.

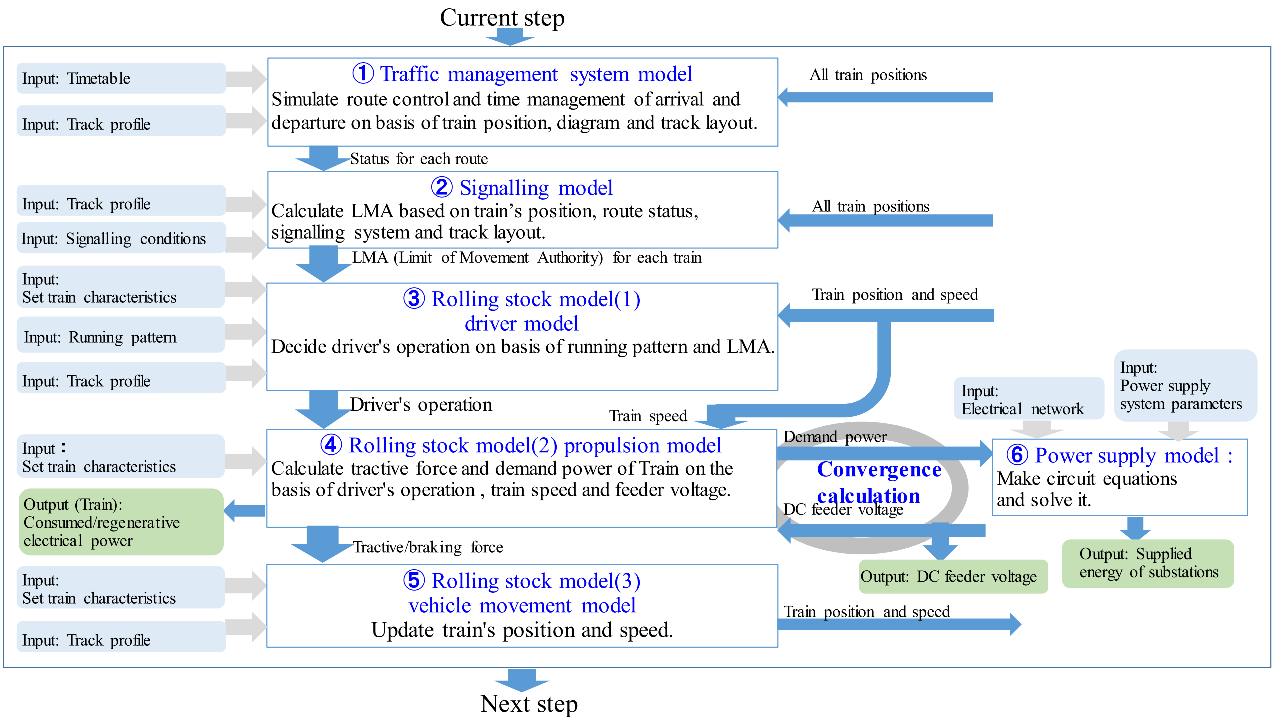



Fig. 2. Simulation flow

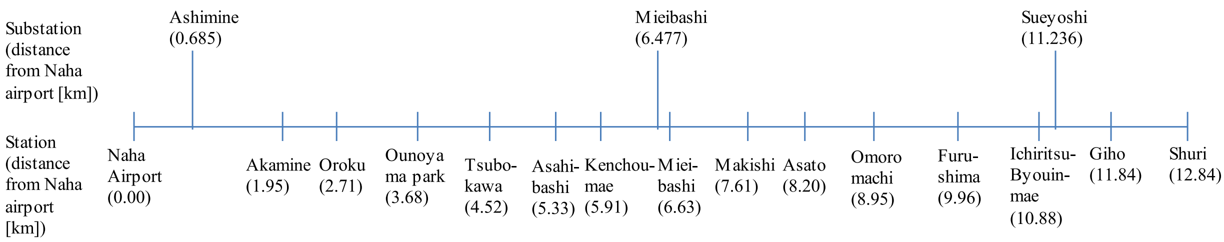



Fig. 3. Okinawa urban monorail

## 3. Measurement with Okinawa Urban Monorail

**3.1 Okinawa Urban Monorail** The Okinawa Urban Monorail is a 12.9 km long monorail system connecting Naha Airport to Shuri station. The maximum speed is 65 km/h, the number of stations is 15, the longest distance between stations is 1.95 km (Naha Airport - Akamine), and the average distance between the stations is 0.92 km. Three substations supply power for train operations. Regenerative power absorption equipment is installed at each substation to prevent regeneration being cancelled by regenerative electric power being consumed when trains cannot absorb the power. The locations of stations and substations on the Okinawa Urban Monorail are shown in Fig. 3.

**3.2 Overview of Measurement Procedure** We carried out the measurements for the cases listed in Table 1 under the condition that Mieibashi substation is out of service. We measured the items listed in Table 2 and Table 3. The measurement data in Table 2 were measured for Train 1, while only running speed was measured by a GPS logger for Train 2. The data in Table 3 were measured for two substations, Ashimine and Sueyoshi.

Table 1. Measurement conditions

| Case | Movement of Train 1 (measured cars) | Movement of Train 2 |
|---|---|---|
| 1 | Akamine ⇒Oroku | Onoyama Park ⇒Oroku |
| 2 | Oroku ⇒Onoyama Park | Oroku ⇒ Akamine |
| 3 | Akamine ⇒Oroku | Oroku ⇒Akamine |
| 4 | Akamine ⇒Oroku | Onoyama Park ⇒Oroku |
| 5 | Oroku ⇒Onoyama Park | Oroku ⇒Akamine |
| 6 | Akamine ⇒Oroku | Oroku ⇒Akamine |
| 7 | Oroku ⇒Onoyama Park | Oroku ⇒ Akamine |
| 8 | Oroku ⇒Onoyama Park | Between Akamine and Naha Airport ⇒Naha Airport |
| 9 | Oroku ⇒Onoyama Park | Akamine ⇒Oroku |

## 4. Comparing Simulation Results and Measurement Data for Okinawa Urban Monorail

The measurement data acquired during the above described measurements on the trains and substations of the Okinawa

Table 2. Measurement data for Train 1

| Parameters |
|---|
| Overhead voltage of train |
| Current flowing through inverter |
| Current flowing in auxiliary equipment |
| Speed |
| Operational commands (handling throttle notch of train except braking step) |
| Load compensating command (train occupancy rate) |
| Brake effort command |
| Actual electric brake effort |
| Filter condenser voltage |

Table 3. Measurement data for substations

| Item | Overview |
|---|---|
| Receiving voltage | Voltage from receiving substation |
| Primary current of rectifier | Current on receiving side of rectifier. |
| Primary current of transformer | Current flowing from substation to incidental facilities (such as stations) |
| DC feeder voltage | Substation voltage |
| Secondary current of rectifier | Current from substation to overhead line |

Table 4. Input simulation conditions

| Item | Overview |
|---|---|
| Timetable | Set on basis of actual measurements |
| Rolling stock characteristics (except running resistance) | Provided by customers |
| Running resistance | Designated on basis of actual measurements |
| Running patterns | Designated on basis of actual measurements |
| Rectifier characteristics in substations | Designated on basis of actual measurements |
| Signalling system | Provided by customers |
| Track profile | Provided by customers |

Urban Monorail were compared with the results of a simulation of running trains with Railway Total Simulator. The conditions regarding the simulation are described in Section 4.1. The method used for the comparison is explained in Section 4.2. The results of comparing the simulation results and measurement data are described in Section 4.3.

**4.1 Input Conditions of Simulation** The rail conditions used in the actual measurements, timetable data, rolling stock characteristics, power supply conditions, and signalling conditions were input into Railway Total Simulator, and a simulation was executed. The input condition items are listed in Table 4.

The departure time and arrival time at each station for the cases listed in Table 1 were set on the basis of the measured time.

Comparing the rolling stock tractive force and electric control force on the basis of the actual measurements with the rolling stock characteristics cited by customers, it was confirmed that the rolling stock tractive force and electric control force are the same as the cited rolling stock characteristics. Accordingly, the cited characteristics were used in the simulation. The running resistance used in the simulation was that given by the following equation on the basis of the actual measurements. It is derived from the least square method and shown in Fig. 4. V is the speed of a train.

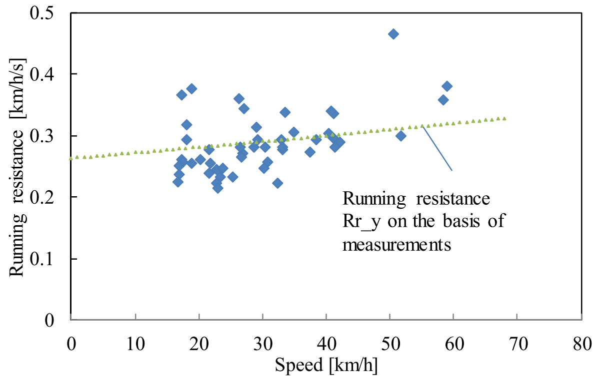
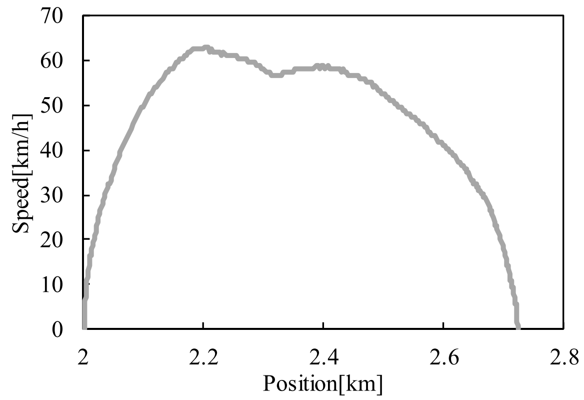


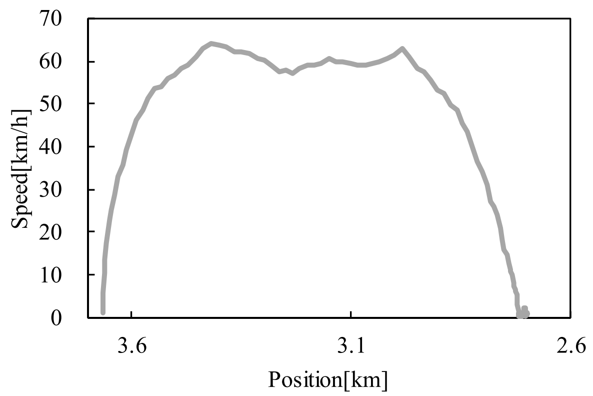

Fig. 4. Running resistance

$$Rr\_y[km/h/s] = 0.2636 + 0.009 \times V + 1.317 \times 10^{-6} \times V^2$$

As for Trains 1 and 2, running patterns were designated on the basis of actual measurements, and running behaviour was simulated in the manner shown in Fig. 5(a) and Fig. 5(b). The rectifier characteristics in a substation were designated on the basis of the actual measurements. They are shown in Fig. 6. The signalling system and track profiles were provided by




(a) Train 1




(b) Train 2

Fig. 5. Example of running pattern (case 1)

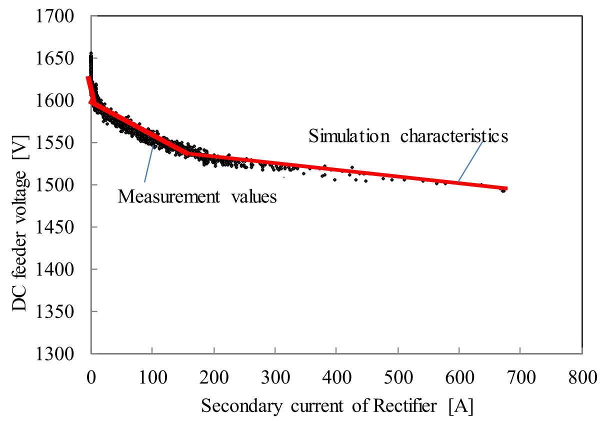



Fig. 6. Rectifier characteristics

customers. In this simulation, the input data of the signalling system were the arrangement of the track circuit and point machine, which is needed for setting the upper limit speed for each track circuit. Moreover, the signalling system decides LMA and the speed limit of each train from the interval between the position of each train and the position where each train can enter, which is determined from the position of the preceding train for each train and the open state of the point machine. Therefore, it is possible to calculate energy consumption under various conditions considering the behaviour of other trains and timetables.

### 4.2 Method for Calculating Difference Estimation

As for the actual comparison, the power amounts in each case were calculated by the simulation and determined from the measurements, and differential values between the measurement data and the simulation output data were calculated as a difference estimation. The target measurement runs were those listed in Table 1. Moreover, the average running distance of each case was short, i.e., less than 1 km, so the total difference, which combines the errors for the evaluation targets of all cases, was calculated. Hereafter, the method used for calculating the difference for each case and the method used for calculating the total difference are explained.

(1) Error estimation method

The electrical energy exerted during each case and the regenerative electric power as well as the power supplied by a substation are calculated as:

$$\mathrm{Energy(i)} = \sum_{t=\mathrm{test_i\_start}}^{\mathrm{test_i\_end}} (\mathrm{Power(i, t)} \times \mathrm{mp} \div 3600) \cdots\cdots (1)$$

where i is the case number, t is time (where $\mathrm{test_i\_start}$ and $\mathrm{test_i\_end}$ represent the start and finish times of case i), mp is the measurement time in seconds [calculation period(s) in the case of the simulation output data], Energy(i) is the amount of energy used in case i [kWh], and Power(i,t) [kW] is the power consumed in time t in case i [kW]. Note that the measurement period for each train and the simulation calculation period were 0.2 s, so *mp* was set to 0.2 s in Equation (1), and the measurement period for the substations was 1 s, so *mp* was set to 1 s in that case.

It is enough to evaluate energy consumption with data measured every second. However, to model the running behaviour of a train, more detailed data are required. Therefore, we measured train data every 0.2 seconds in this measurement. To compare the simulation results of running behaviour and measured data of running behaviour, we carried out the simulation by using every 0.2 seconds.

(2) Estimating total difference

The above stated parameters in each case were calculated in the simulation and the measurements, and the difference in each case was estimated by using Equation (2). The cases targeted were those listed in Table 1. The total difference (including the differences for each case) is given as:

$$\mathrm{Difference(i)} = \frac{\mathrm{Energy\_m(i)} - \mathrm{Energy\_s(i)}}{\mathrm{Energy\_m(i)}} \cdots\cdots (2)$$

$$\mathrm{Difference_{average}} = \frac{\sum_{i=\{1to9\}} |\mathrm{Energy\_m(i)} - \mathrm{Energy\_s(i)}|}{\sum_{i=\{1to9\}} \mathrm{Energy\_m(i)}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where i is the case number, Energy_m(i) is the electrical energy measured in case i [kWh], Energy_s(i) is the electrical energy calculated by the simulator for case i, difference is the estimated electrical power error ratio for case i, and Difference_average is the total (average) estimated electrical power error ratio for all cases.

### 4.3 Comparing Measurement and Simulation Results

The measurement results for Train 1 and each substation are compared with the simulation results as explained in the following.

(1) Comparing measurements performed on rolling stock

The results of estimating the differences on the basis of the methods described in Sections 4.2 for Train 1 are listed in Table 5 and Table 6. The total differences in the simulation and measurement data for the consumed electrical energy and regenerative electrical power of the rolling stock were 3.6% and 3.9%.

Moreover, listed in Table 7 are the comparisons of the average value of the acceleration rate, deceleration rate, peak power, peak regenerated power, maximum voltage, minimum voltage and average voltage for all test cases for Train 1 between the measurement data and the simulation output data. The average differences in the simulation and measurement data for the acceleration rate, deceleration rate, peak power, peak regenerated power, maximum voltage, minimum voltage and average voltage of the rolling stock were 2.7%, 6.4%, 4.7%, 4.0%, 2.1%, 2.2% and 0.4%.

(2) Comparing measurements performed at substations

In regard to the energy supplied at the Ashimine and Sueyoshi substations, the results of estimating the differences with the methods described in Section 4.2 for the substations are listed in Table 8 and Table 9.

The total differences in the simulation and measurement data for energy supplied at Ashimine substation and Sueyoshi substation are 5.5% and 2.9%.

Moreover, listed in Table 10 are the comparisons of the average value of the maximum voltage, minimum voltage and average voltage for each substation for all test cases between the measurement data and the simulation output data. The average differences in the simulation and measurement data for maximum voltage, minimum voltage and average voltage for Ashimine substation were 3.2%, 0.5% and 0.3%. The average differences in the simulation and measurement data for

Table 5. Comparison of measurement data and simulation for consumed electrical energy of Train 1

| Case | Measurement [kWh] | Simulation [kWh] | Difference [kWh] | Difference [%] |
|---|---|---|---|---|
| 1 | 4.10 | 3.99 | 0.11 | 2.7% |
| 2 | 2.29 | 2.46 | 0.17 | -7.5% |
| 3 | 3.78 | 3.68 | 0.09 | 2.5% |
| 4 | 3.11 | 3.15 | 0.04 | -1.2% |
| 5 | 1.98 | 1.98 | 0.00 | -0.1% |
| 6 | 3.02 | 3.10 | 0.08 | -2.7% |
| 7 | 2.49 | 2.57 | 0.09 | -3.5% |
| 8 | 2.41 | 2.57 | 0.16 | -6.6% |
| 9 | 1.84 | 1.98 | 0.15 | -8.1% |
| Total | 25.00 | 25.49 | 0.89 | 3.6% |

Table 6. Comparison of measurement data and simulation for regenerative electrical energy of Train 1

| Case | Measurement [kWh] | Simulation [kWh] | Difference [kWh] | Difference [%] |
|---|---|---|---|---|
| 1 | 0.95 | 1.02 | 0.07 | -7.7% |
| 2 | 3.19 | 3.34 | 0.15 | -4.8% |
| 3 | 0.80 | 0.80 | 0.00 | -0.2% |
| 4 | 0.95 | 0.98 | 0.03 | -3.7% |
| 5 | 2.79 | 2.76 | 0.02 | 0.9% |
| 6 | 1.06 | 1.04 | 0.02 | 2.3% |
| 7 | 3.29 | 3.46 | 0.17 | -5.3% |
| 8 | 3.34 | 3.49 | 0.15 | -4.4% |
| 9 | 2.70 | 2.82 | 0.12 | -4.3% |
| Total | 19.07 | 19.72 | 0.75 | 3.9% |

Table 7. Comparison of measurement data and simulation for average value of each parameter for all test cases of Train 1

| Parameter | Measurement | Simulation | Summation of difference (%Difference) |
|---|---|---|---|
| Acceleration rate | 3.16 km/h/s | 3.09 km/h/s | 0.08 km/h/s (2.7%) |
| Deceleration rate | 2.23 km/h/s | 2.33 km/h/s | 0.14 km/h/s (6.4%) |
| Peak power | 959.20 kW | 1003.47 kW | 45.32 kW (4.7%) |
| Peak regenerated power | 481.78 kW | 475.82 kW | 19.32 kW (4.0%) |
| Maximum voltage | 1676.58 V | 1710.82 V | 34.71 V (2.1%) |
| Minimum voltage | 1435.56 V | 1403.48 V | 32.07 V (2.2%) |
| Average voltage | 1589.93 V | 1583.91 V | 6.02 V (0.4%) |

Table 8. Comparison between measurement data and simulation for energy supplied at Ashimine substation

| Case | Measurement [kWh] | Simulation [kWh] | Difference [kWh] | Difference [%] |
|---|---|---|---|---|
| 1 | 7.38 | 7.59 | 0.21 | -2.9% |
| 2 | 3.88 | 4.18 | 0.30 | -7.9% |
| 3 | 4.74 | 4.84 | 0.09 | -1.9% |
| 4 | 5.01 | 5.21 | 0.20 | -4.1% |
| 5 | 3.47 | 3.73 | 0.26 | -7.4% |
| 6 | 4.31 | 4.64 | 0.33 | -7.6% |
| 7 | 3.23 | 3.35 | 0.12 | -3.8% |
| 8 | 3.75 | 4.13 | 0.38 | -10.2% |
| 9 | 3.57 | 3.84 | 0.27 | -7.5% |
| Total | 39.35 | 41.51 | 2.17 | 5.5% |

Table 9. Comparison between measurement data and simulation for energy supplied at Sueyoshi substation

| Case | Measurement [kWh] | Simulation [kWh] | Difference [kWh] | Difference [%] |
|---|---|---|---|---|
| 1 | 3.83 | 3.63 | 0.20 | 5.1% |
| 2 | 1.78 | 1.78 | 0.00 | 0.0% |
| 3 | 2.00 | 1.88 | 0.12 | 6.2% |
| 4 | 2.38 | 2.33 | 0.05 | 2.1% |
| 5 | 1.59 | 1.58 | 0.01 | 0.7% |
| 6 | 1.82 | 1.82 | 0.00 | 0.1% |
| 7 | 1.66 | 1.61 | 0.05 | 3.0% |
| 8 | 1.46 | 1.39 | 0.07 | 4.6% |
| 9 | 1.54 | 1.52 | 0.03 | 1.7% |
| Total | 18.05 | 17.53 | 0.52 | 2.90% |

Table 10. Comparison of measurement data and simulation for average value of maximum voltage, minimum voltage and average voltage for all test caoses at Ashimine substation

| Case | Measurement [V] | Simulation [V] | Difference [V] | Difference [%] |
|---|---|---|---|---|
| Maximum | 1657.11 | 1708.65 | 53.53 | 3.2 |
| Minimum | 1480.56 | 1472.82 | 7.73 | 0.5 |
| Average | 1594.24 | 1592.43 | 4.55 | 0.3 |

Table 11. Comparison of measurement data and simulation for average value of maximum voltage, minimum voltage and average voltage for all test caoses at Sueyoshi substation

| Case | Measurement [V] | Simulation [V] | Difference [V] | Difference [%] |
|---|---|---|---|---|
| Maximum | 1650.33 | 1709.34 | 59.01 | 3.6 |
| Minimum | 1503.11 | 1500.91 | 4.67 | 0.3 |
| Average | 1594.34 | 1597.41 | 5.11 | 0.3 |

maximum voltage, minimum voltage and average voltage for Sueyoshi substation were 3.6%, 0.3% and 0.3%.

## 5. Consideration

**5.1 Total of Substation Energy** In Section 4.3, it was shown that the difference between the measurement and simulation values for each substation was within 6%. However, it was confirmed that the measurement value for Ashimine substation's supplied energy was lower than the simulation value, and the measurement value of Sueyoshi substation's supplied energy was more than the simulation value in the case of all measurements. It is thought that the reason is the

Table 12. Comparison between measurement data and simulation for supplied energy of two substations

| Case | Measurement [kWh] | Simulation [kWh] | Difference [kWh] | Difference [%] |
|---|---|---|---|---|
| 1 | 11.21 | 11.22 | 0.02 | -0.1% |
| 2 | 5.66 | 5.97 | 0.30 | -5.4% |
| 3 | 6.74 | 6.71 | 0.03 | 0.5% |
| 4 | 7.39 | 7.54 | 0.15 | -2.1% |
| 5 | 5.07 | 5.31 | 0.25 | -4.9% |
| 6 | 6.13 | 6.46 | 0.33 | -5.3% |
| 7 | 4.88 | 4.95 | 0.07 | -1.5% |
| 8 | 5.20 | 5.52 | 0.32 | -6.1% |
| 9 | 5.11 | 5.35 | 0.24 | -4.7% |
| Total | 57.40 | 59.04 | 1.71 | 3.0% |

difference of feeder resistance and balance of supplied power at each substation. We compared the differences between the simulation and measurement data for the total supplied energy of the substations, shown in Table 12. The differences between the simulation and measurement data with were improved to 3.0%.

It is believed that this evaluation method is sufficient for evaluating the total energy in a rail line. It is necessary to measure the feeder resistance at least when we evaluate the accuracy of prediction energy consumption for each substation.

**5.2 Behaviour of Trains and Substations** As for the comparison between the measurement data and simulation result of case 1, the running patterns of Train 1 and 2 are shown in Figs. 7(a) and (b). The behaviours were fairly similar. The amounts of electrical power consumed by the rolling stock and regenerative power are shown in Fig. 7(c), and the feeder voltage of Train 1 is shown in Fig. 7(d). The calculated (simulation) values were close to the measured ones.

As shown in Table 7, the average value of the acceleration rate, deceleration rate, peak power, peak regenerated power, maximum voltage, minimum voltage and average voltage of the rolling stock for all test cases were within 6.4%. This accuracy is equivalent to the accuracy of the energy consumption of Train 1. From the above, it is considered that this simulator can simulate the energy consumption of a train with sufficient accuracy.

Moreover, as shown in Figs. 8(a), (b) and (c), the behaviours were fairly similar in regard to the behaviour of the electrical power supply at the substations.

The difference in consumed electrical power in the case of Train 1 for case 1 was 2.7%, as shown in Table 5; in contrast, the differences in the substation electrical power supply amount at the Ashimine and Sueyoshi substations were −2.9% and 5.1%, as shown in Table 8 and Table 9, respectively. From the standpoint of energy regeneration, the difference in regenerated electrical power for Train 1 was −7.7%, as shown in Table 6.

As shown in Table 10 and Table 11, the average values of the maximum voltage, minimum voltage and average voltage of each substation for all test cases were within 3.6%. The calculated (simulation) values for the substations were also close to the measured ones.

It was concluded that power consumption can be predicted at a sufficient accuracy when calculating design indices for both rolling stock and substations.

The following can be considered as reasons for the agreement. Our railway total simulator models physical models such as trains and substations in detail by using multiple parameters, as discussed in Section 2. In addition, we calculated parameters for running resistance on the basis of the measured data by using the least square method. We used the equation of running resistance in the simulation. In the same way, we measured substation data every 0.2 seconds and modelled the rectifier characteristics for substations. This is the reason that the simulation result and measured data were comparatively well matched.

**5.3 Analyzing Difference between Measurement Data and Simulation** In Section 5.2, it was shown that, as a result of comparing the simulation with the measurement data for case 1, the item that made the maximum difference was Train 1's regenerative electric power. When the behaviour of Train 1's regenerative power was confirmed, it became clear that a difference between the simulation and measurement data was generated around 1300 sec and after 1320, as shown in Fig. 7(c). It is thought that the reason for the difference is the difference in braking control.

We did not measure the brake notch in this measurement. Therefore, we chose for the brake notch to follow a measured running pattern. Because this selection does not completely accord with the measurement, it is thought that this is one reason that difference occurred.

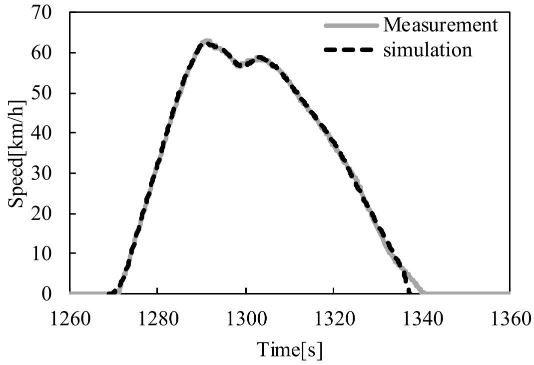
It will be necessary to measure the brake notch and develop a highly accurate technique for choosing a brake notch on the basis of a measured brake notch and running pattern when we further improve accuracy.

**5.4 Application to General Railway** In this paper, the results of measurements performed on the Okinawa Urban Railway were compared with corresponding simulation results by Railway Total Simulator. A point of note is that the Okinawa Urban Railway has specifications that differ to those of a general heavy railway line.

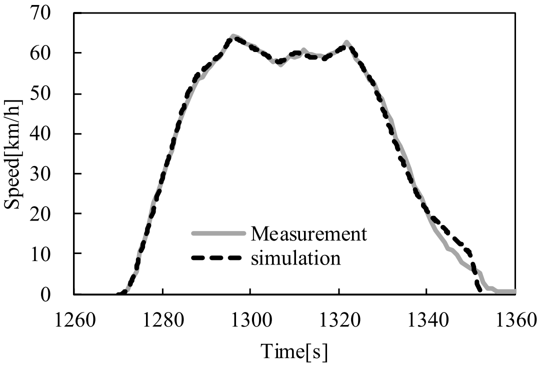
Looking from a physical point of view, the differences between rubber-tire-driven monorails and popular iron-wheel-driven trains are vehicle appearance, track shape, how power is exchanged and so on. These are shown in Table 13. However, these elements are parameters for executing the simulation.

Therefore, the simulator is applied to other vehicles and other lines, because it is possible to calculate energy consumption with the same precision by selecting the parameters appropriately. The point that one should be careful about is particularly running resistance. Running resistance varies with the vehicle configuration and the friction state between a vehicle and the ground. It is different from a monorail traveling on a concrete girder with rubber tires and a general railway vehicle that runs with iron rings on two running rails. Our developed simulator is setable with the equation for running resistance. We think that it is applicable to public railway vehicles by using the equation on the basis of the measured data as carried out this time.

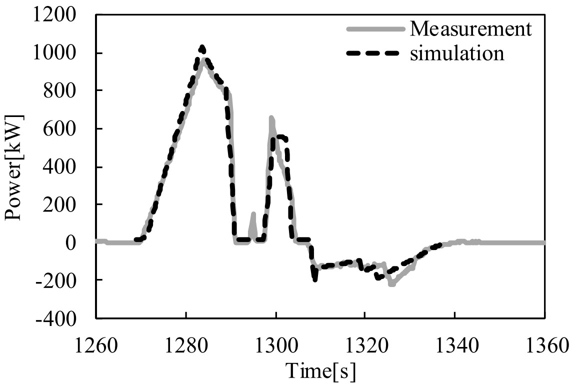
We would like to consider this application in the future.



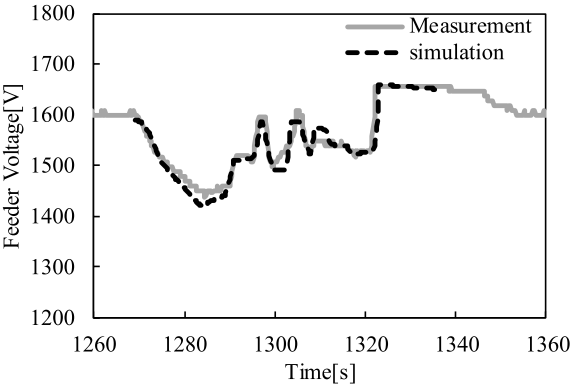

(a) Running pattern of Train 1




(b) Running pattern of Train 2

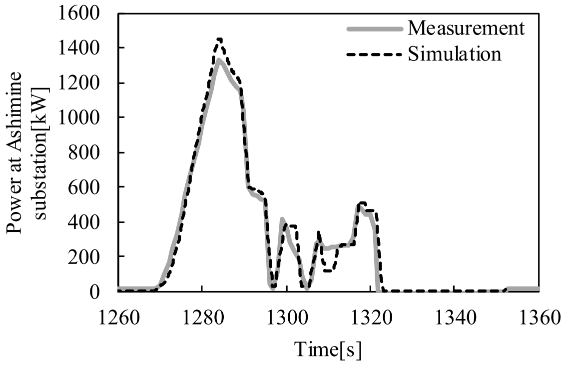



(c) Consumed and regenerative power

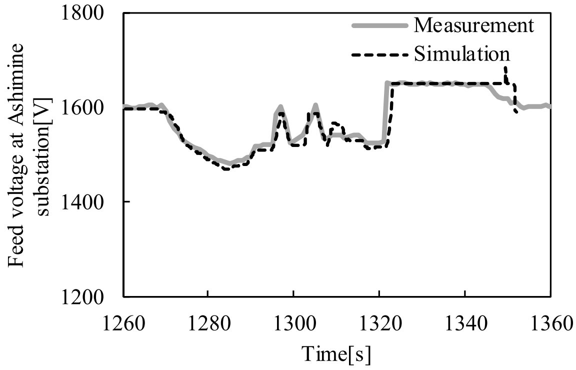



(d) Feeder voltage

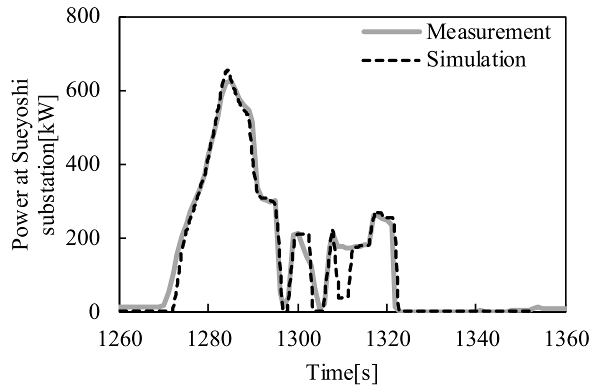
Fig. 7. Comparison of measurement data and simulation result of train for case 1



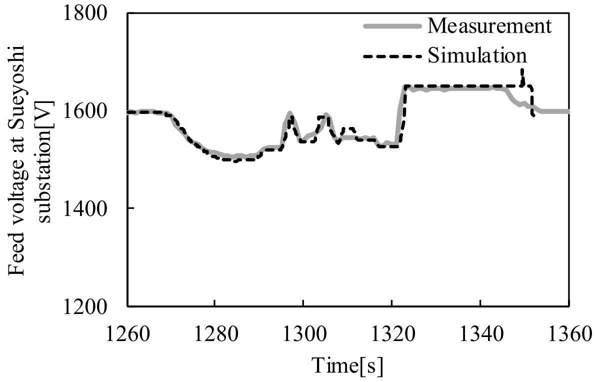

(a) Power at Ashimine substation




(b) Feed voltage of Ashimine substation




(c) Power of Sueyoshi substation




(d) Feed voltage of Sueyoshi substation

Fig. 8. Comparison of measurement data and simulation result of each substation for case 1

## 6. Concluding Remarks

The results of comparing measurements performed on the Okinawa Urban Railway with corresponding simulation results obtained by Railway Total Simulator are summarized as follows. It was confirmed that the simulation can predict power behaviour with a sufficient accuracy on railway lines carrying running trains and that the average simulation

Table 13. Comparison of monorail system and general railway system

| | Monorail | General railway system |
|---|---|---|
| Driving method | Motor using electric power supplied by power supply equipment | Motor using electric power supplied by power supply equipment |
| Railway track | Concrete girder | Two running rails |
| Wheel | Multiple rubber tires | Iron rings |
| Power exchange | Third rail | Catenary/third rail |

differences were 3.6% for rolling stock power consumption, 3.9% for rolling stock regenerative power, and 3.0% for substation power supply.

The following can be considered as reasons for the agreement. Our railway total simulator models physical models such as trains and substations in detail with multiple parameters. We calculated the parameters of running resistance on the basis of measured data by using the least square method. We used an equation for running resistance in the simulation. In the same way, we measured substation data every 0.2 seconds and modelled the rectifier characteristics for substations. This is the reason that the simulation results and measured data were comparatively well matched. It was concluded from these results and from the similarity between the monorail and a general railway that it is possible to obtain a sufficiently low difference in the results of a comparative investigation on the basis of a calculation that is similar to that for calculating energy for railways with general DC power systems with Railway Total Simulator on an overall railway with a DC power system.

To check accuracy, we will check the simulation accuracy for a general railway in the future.

**Acknowledgment**

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## References

( 1 ) "Sustainability Report 2009", East Japan Railway Company (2009)

( 2 ) M. Suzuki, T. Miyauchi, and Y. Nakamura: "Development of Railway Total Simulator", 48th Cybernetics Symposium, No.103 (2011) (in Japanese)

( 3 ) Y. Takeuchi, T. Ogawa, H. Morimoto, Y. Imamura, S. Minobe, H. Miyaguchi, J. Kawamura, K. Hayashida, N. Shimada, T. Yamanoi, and S. Manabe: "Additional Verification for Coupled-Analysis Traction Power Simulation System by Energy Consumption Measurement Examination", Joint Technical Meeting on "Transportation and Electric Railway" and "Linear Drives", IEE Japan, TER-15-028/LD-15-019 (2015) (in Japanese)

( 4 ) T. Miyauchi, K. Tokuyama, H. Takahashi, and T. Kuroshima: "Preparations for Development of Energy Management System Integrating Wayside Devices and On-board Systems—Accuracy Testing of Railway Total Simulator based on Energy-use Analysis of Okinawa Urban Monorail Line", Hitachi Review, Vol.63, No.10, pp.684–689 (2014)

( 5 ) T. Ogawa, Y. Takeuchi, H. Morimoto, T. Yoshii, Y. Imamura, and M. Kageyama: "Verification of a Train Traction Power Simulator for DC Feeding System by a Commercial Operation Measurement", Electrical Systems for Aircraft Railway Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC) International Conference on, pp.1–6 (2016)

( 6 ) A. Stephan: "OpenPowerNe—Simulation of Railway Power Supply Systems", Comprail 2008 (2008)

( 7 ) Y. Suzuki, K. Onishi, H. Yamashita, K. Morita, N. Yanai, and M. Mitake: "Integrated APM/LRT Simulator for Energy Evaluation", Mitsubishi Heavy Industries Technical Reports, Vol.47, No.2, pp.2–6 (2010) (in Japanese)

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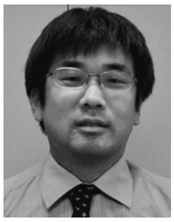

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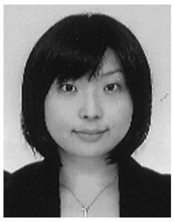

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