Developments in Electric Power and CO$_2$ Reduction on the Japanese Railway

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Abstract: The author would like to speak about how Japanese railway companies are trying to reduce electric power consumption by electric traction train. In other word, a reduction in petroleum / natural gas, and CO$_2$ discharge. This paper only dealt with electric train, Shinkansen, commuter train, and subway train not deal with electric / diesel engine locomotives.

Key words: Electric power reduction, CO$_2$ discharge reduction, high speed train, commuter train, subway train, PWM-VVVF converter.

1. Electric power generation and CO$_2$ discharge in Japan

The author knows that the circumstances of the railway system and electric power generation is different in Japan and the Czech Republic. But the ultimate future target of both countries is the same: “Minimize petroleum / natural gas consumption and the reduction of CO$_2$ discharge“

Total generated electric power in 2004 was 1,137 Billion kwh. This means the consumed electric power in 2004 per head was $\approx 9,000$ kwh. About 66 % of the generated electric power came from steam turbine generators. That is to say, it came from imported petroleum, natural and coal. In other word, the amount of discharged CO$_2$ for electric power is proportional to $\approx 66$ % of the generated electric power.

Electric power consumed by railway transport is just only $\approx 1.9$ % of the total, that is $\approx 21.6$ % Billion Kwh (2004). The total volume of discharged CO$_2$ in 2003 was $\approx 1,259$ Million tons. As far as railway transport is concerned, it is assumed that the CO$_2$ discharged by the railway transport is $\approx 7.8$ Million tons in 2003. The amount of discharged CO$_2$ is closely related to petroleum / natural gas consumption. From these data, it is roughly assumed that relation between discharged CO$_2$ and consumed Kwh is $\approx 350$ gr / Kwh in railway transport.

Every petroleum / natural gas consumers, including railway companies is trying to reduce petroleum / natural gas consumption, that is to reduce CO$_2$ discharge. The motivation for reduction activities is to achieve the target of “Kyoto Congress Resolution 1997”, and to reduce energy costs (increase profits).
2. Electric power reduction of the railway transport sector

The author would like to introduce items and developments in electric power reduction of three groups of electric trains in the following section.

2.1. General

In order to reduce the electric power consumption of electric powered cars / trains, the following items should be taken into account.

1) Decrease in the weight of car / train (necessitate for all kinds of train)
   Reduction of car / train weight is essential for the reduction of electric power consumption not only for acceleration but also top speed running.

2) Efficient motor control system (necessitate for commuter and subway trains)
   Higher efficient methods of power conversion from train motion energy to electric power and feedback the power to the power line (AC 25 kV 50/60 Hz or DC 1500V) during deceleration are required.

3) Adequate train running pattern (necessitate for Shinkansen Train)
   At the start, accelerate the train to the top running speed within the shortest time, then keep top speed with inertia and lower electric power for long distances. When stopping the train, convert the train motion energy to electric power and feedback to power line with the largest amount of motion energy by converter with novel (vector) control.

4) Decrease of running (air resistance) loss (necessitate for Shinkansen train)
   For high speed train, air resistance loss is proportional to the square of the running speed. When designing high speed trains, the shape of the front and tail car, smooth body surface, bottom cover and also shape and number of pantographs should be considred.

Practical electric power reduction for trains will be obtained not from one item but usually from some items combined together.

2.2. Shinkansen train (high speed and long distance)

Currently, five Shinkansen lines are operating and the lines are played and playing a great role in Japan’s economical development. The number of Shinkansen passengers in 2003 was ≈ 283 Million. At present, five more new Shinkansen line are under construction.

Figure 1 shows present train Type “700”, formation and drive circuit.

![Figure 1 Eerodynamic shape of Type “700” and formation, drive circuit.](image-url)
1) Decrease of train weight  
   Train weight of present Type “700” (708 tons with 16 cars) is ≈ 73 % of the first Type “0” (970 tons with 16 cars). The weight reduction mainly came from:  
   a) apply rational structure design and change of structure materials from steel to extruded aluminum alloy.  
   b) change from DC motors (Type “0”) to induction motors (Type “700”), and reduction in the number of motors from 64 (Type “0”) to 48 (Type “700”).  
   c) change of motor control from “tap changing with thyristors” (Type “0”) to light weight “PWM-VVVF converter with IGBTs” (Type “700”).

2) High efficient motor control  
   Using high efficient PWM-VVVF converters and novel control, the full motion energy of the train is converted to electric power and sent back to the power line in case of deceleration. This means that very small heat generation occurs at final mechanical breaking.

3) Train running pattern for lower electric power consumption  
   Distance between station to station on the Tokaido Shinkansen Line (in case of “Nozomi”) is ≈ 40 to ≈ 340 km. Adequate running pattern, that is (1) shorter time from zero to the top speed, (2) top speed running with inertia and lower electric power with long distance, (3) then deceleration with full power re-generation within shorter time, is applied for Shinkansen. From this running pattern, ≈ 20 % of electric power reduction per train is obtained.

4) Decrease of running losses  
   Running losses mainly consist of (1) machine (friction) losses and (2) air resistance loss. As result of wind tunnel tests and practical running test, the long nose “duckbill” shape of the front and tail cars, and flat smooth surface of car body (both sides and bottom) are adopted in Type “700”. The running losses (mainly air resistance loss) of Type “700” is reduced to ≈ 63 % of Type “0” at speed of 220 km/h.

   Studies on total electric power consumption, Type “700” is reduced to ≈ 66 % of Type “0” at the same running condition. From this reason, Type “0” is already replaced to Type “700” from Tokaido Shinkansen line.

2.3 Commuter train (frequent start/stop, relatively short distance)
   Total of twelve commuter train lines are operating surrounding and passing through Tokyo and connecting satellite cities outside of Tokyo. The average distance from station to station is ≈ 1-2 km inside Tokyo, and ≈ 3-6 km in the suburbs of Tokyo. Figure 2 shows the resent commuter train Type “E 231”, train formation and converters.

1) Decrease of train weight  
   As the results of applying the technologies of 2.2, 1), the train weight of the new Type “E 231” is reduced to ≈ 70 % of the previous Type “103”.

2) Higher efficient motor control  
   In order to respond to frequent start/stop, 4 sets of PWM-VVVF converters in a Type “E 231” train (consists of 4 cars with motors and 6

Figure 2 The newest Type “E 231” commuter train and formation, drive circuit.
trailers) are controlled coordinately and efficiently for quick acceleration and feedback converted electric power from full of motion energy to the DC 1500 V line.

From the results of development, Type “E 231” is widely used around Tokyo.

2.4 Subway (metro) train

Figure 3 shows a total of thirteen lines of subway network are operating underground in the Tokyo metropolitan area. More than 6 Million people are using subway network every day. Ten of these subway lines are connecting both sides of Tokyo suburbs without changing train at a station. These “direct through subway lines” are very useful and convenient for inhabitants of Tokyo suburbs and other passengers.

Train of every subway line consists of 6-10 cars (all with motor). The distance between each underground station is ≈ 1 km or less. This means a much more frequent start/stop running pattern is required for subway trains than for commuter trains.

1) Decrease of train weight   Applying new technologies and new materials as 2.2, 1), the total train (10 cars) weight of the new Type “05” became ≈ 266 tons, that is, reduced to ≈ 85 % that of the previous type.

2) High efficient motor control    Train speed control is basically the same as the commuter train. Applying new PWM-VVVF converters, the estimated electric power consumption under the definite running pattern is ≈ 60 % that of the previous type, consists of DC motors with resistance speed control during acceleration/deceleration.

3. Summary

As far as amount of CO₂ discharge volume per person-km is concerned, electrical railway (≈ 5 g/person-km) is ≈ 16 % of aircraft, ≈ 18 % of commercial bus. This means electric railway is the lowest CO₂ discharge form of mass transportation. Consumed electric power by electric railway in Japan, is just only ≈ 1.9 % of the total generated electric power (2004).

About 66 % of total generated electric power comes from steam turbine generators that come from imported petroleum, natural gas and coal.

R & D themes of electric power reduction by railway companies are (1) Reduction of car/train weight, (2) More efficient power control, (3) Rational design of car shape.

Japanese researchers and engineers who are involving in this fields are trying to reduce more electric power consumption and reduce of CO₂ discharge.

Appendix    The author recommend to contact the Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji City, Tokyo, Japan. Tel (from Praha) 0081-42-573-7212, Fax (=) 573-7488, for exchange of wide range of knowledge on railway technologies.