ETH Kolloquium 2017/12/07

Energy-saving strategy in automatic train operation

Dept. EEIS
The University of Tokyo

Takafumi KOSEKI

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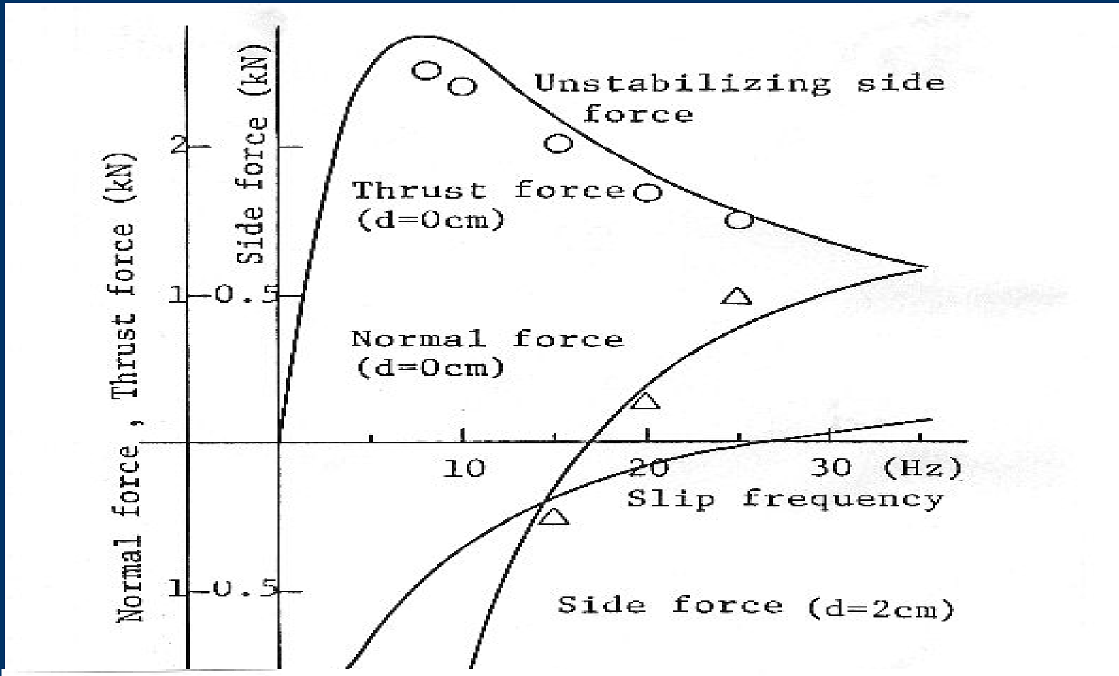
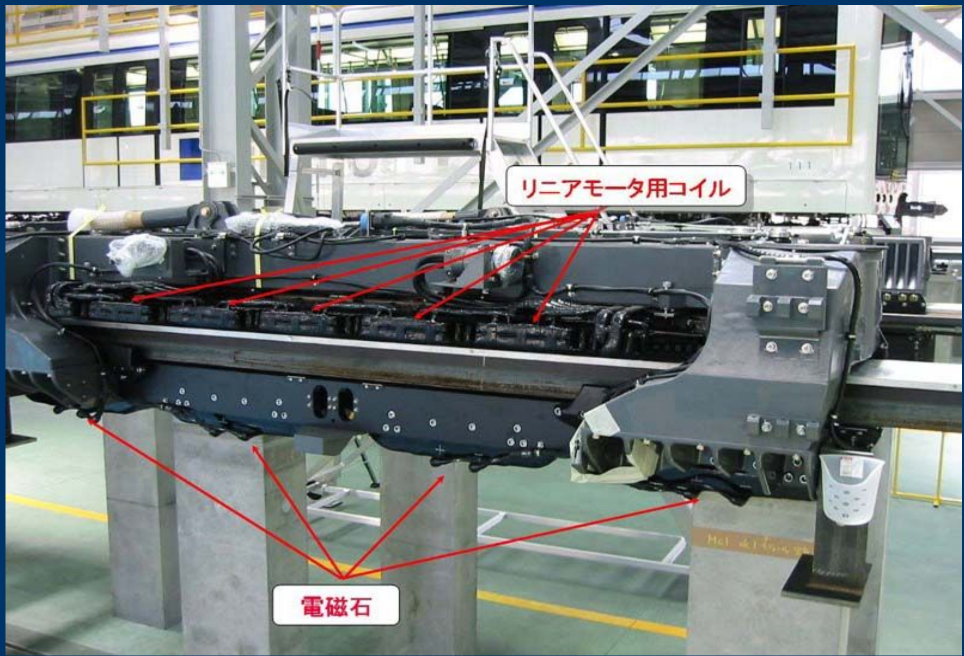
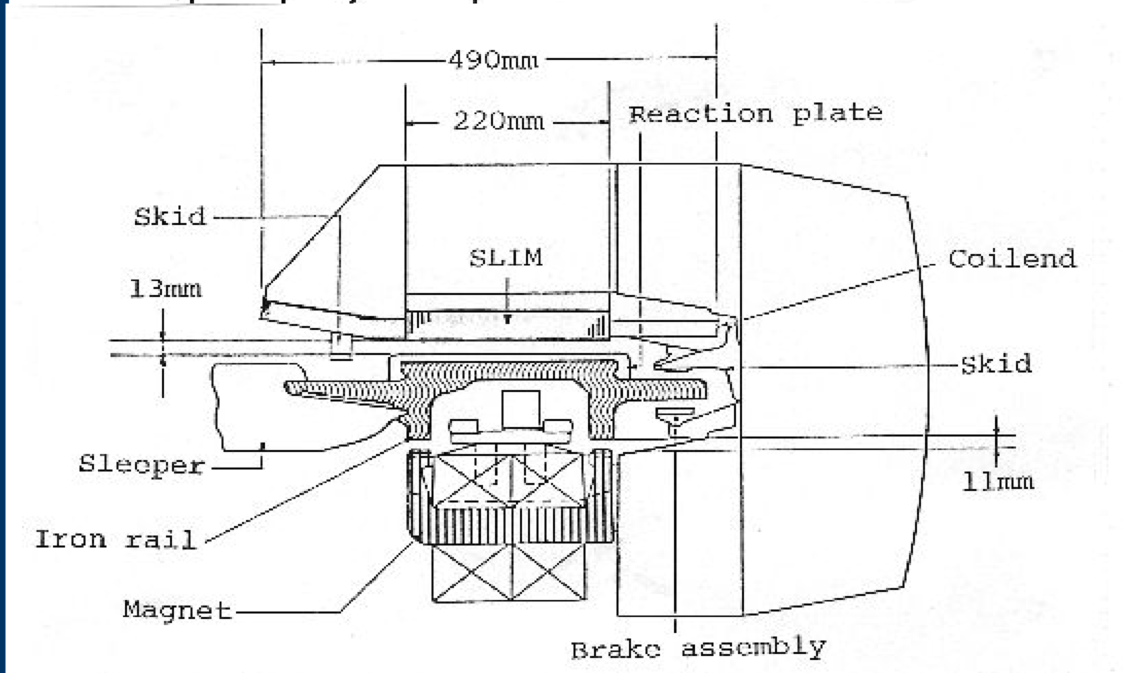
Self-introduction

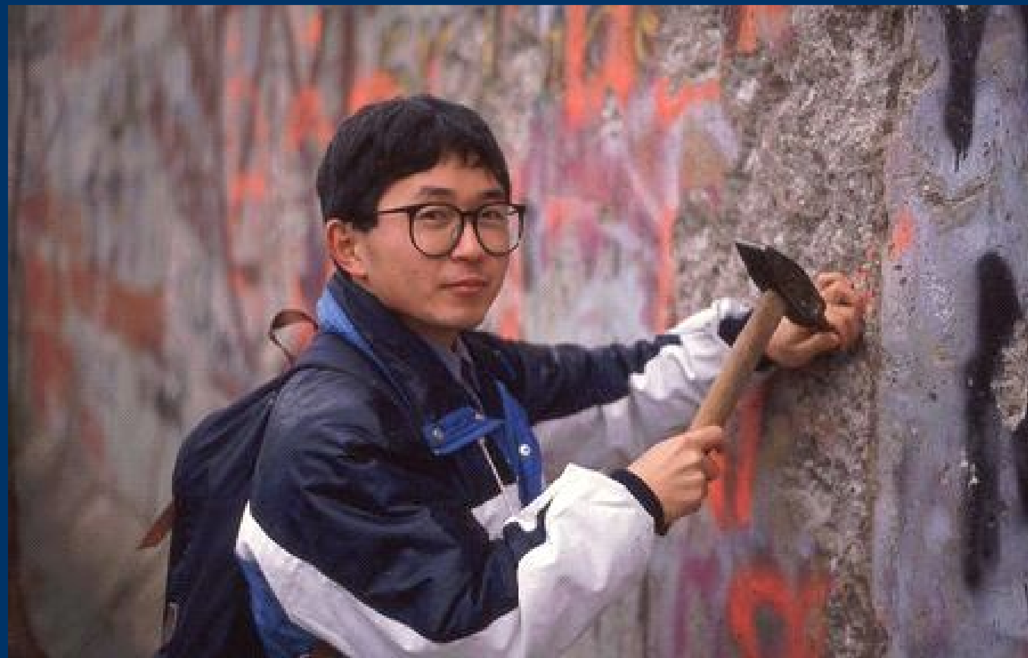
M-Thesis (1988): Magnetic Wheel





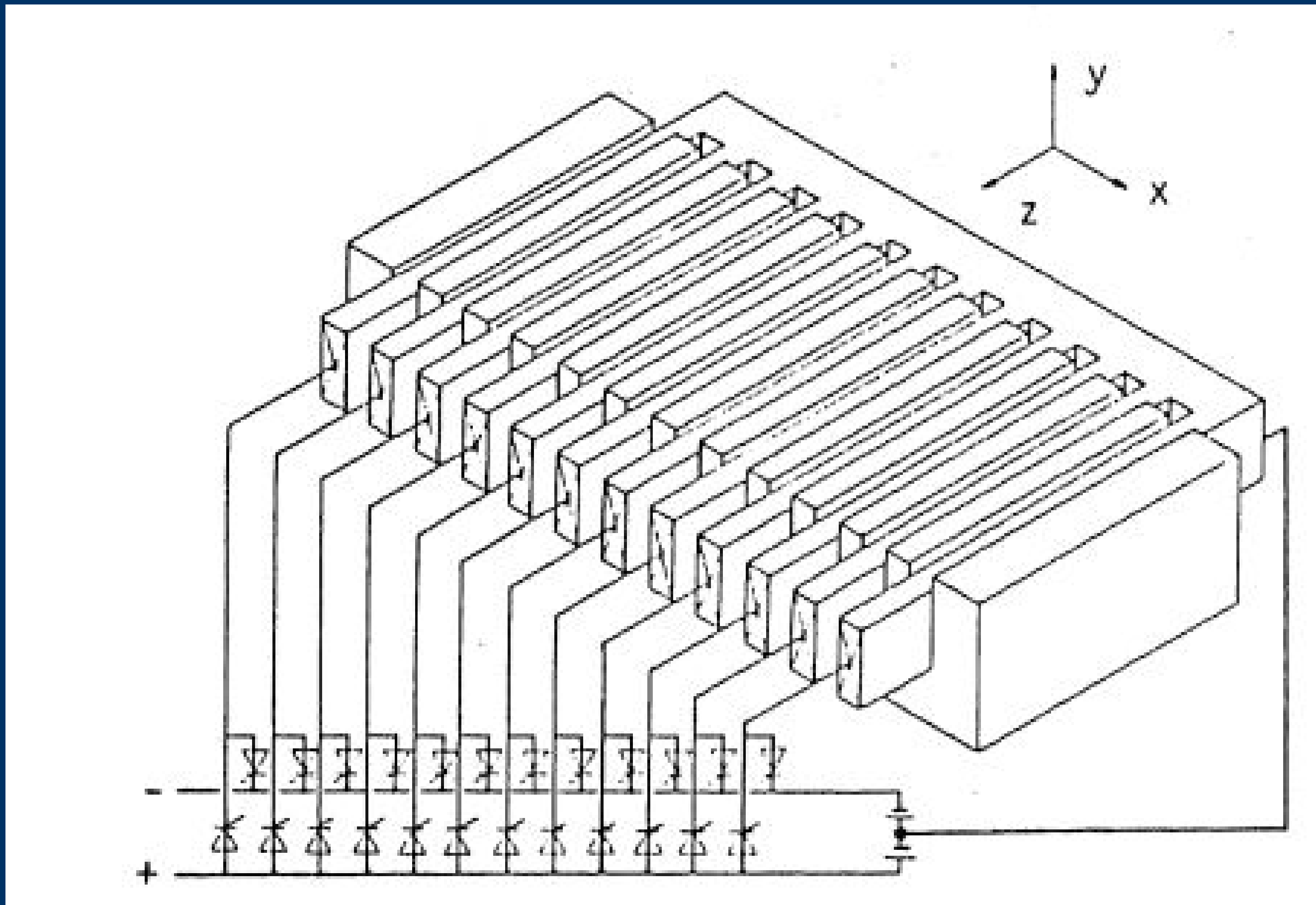


Germany 1989-1990



D-Thesis (1992)：
Flux Synthesizing Linear Induction Motor

$$\frac{\partial}{\partial x}\left[\nu_y \frac{\partial A}{\partial x}\right] + \frac{\partial}{\partial y}\left[\nu_x \frac{\partial A}{\partial y}\right] = -J_0 + \sigma\left\{\frac{\partial A}{\partial t} + v_2 \frac{\partial A}{\partial x} + \frac{\partial \phi}{\partial z}\right\}$$



ETH-UOT: The first Swiss contacts 1994?


THE AGS
The Alliance for Global Sustainability

Swiss Federal Institute of Technology	The University of Tokyo	Massachusetts Institute of Technology	Chalmers University of Technology
09:05	17:05	04:05	09:05

18 Mar 2015

Home
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Outreach

Highlight:

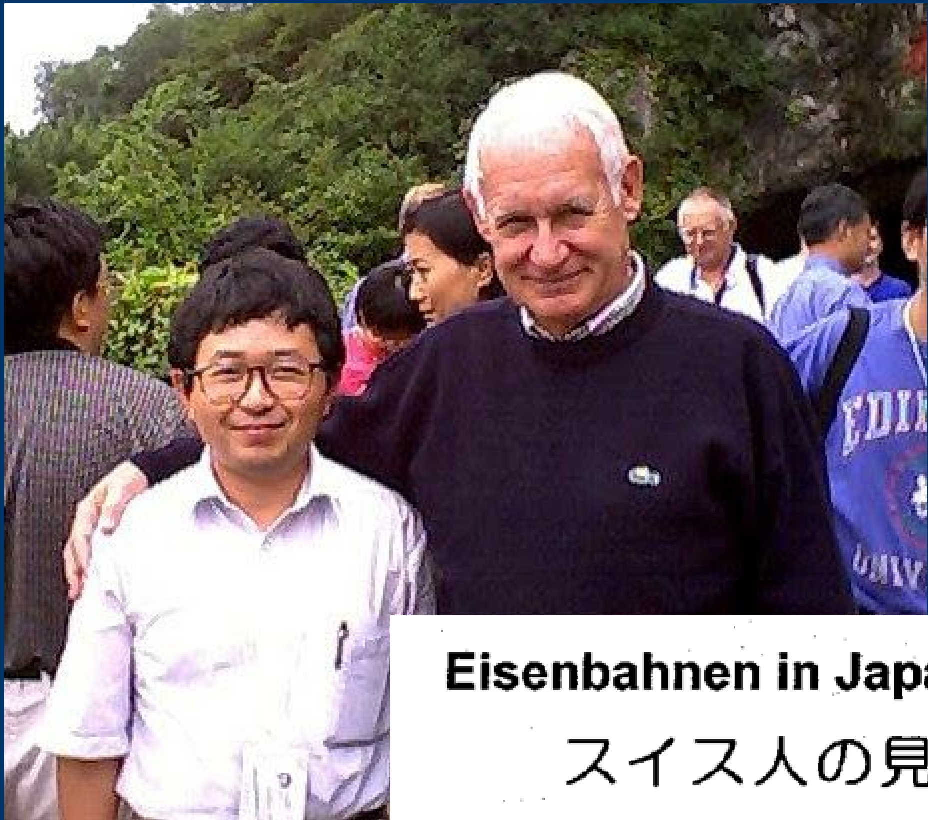
The AGS project is to be re-started during 2014

The project is no longer active in its current formation.

If any questions please contact: thomas.pettersson@chalmers.se

Prof. Y. Hori and T. Koseki **Prof. Lino Guzzella**

ETH, SBB, and Swiss contacts 1996-



Eisenbahnen in Japan - aus Schweizer Sicht

スイス人の見た日本の鉄道

Beobachtungen im November 1996

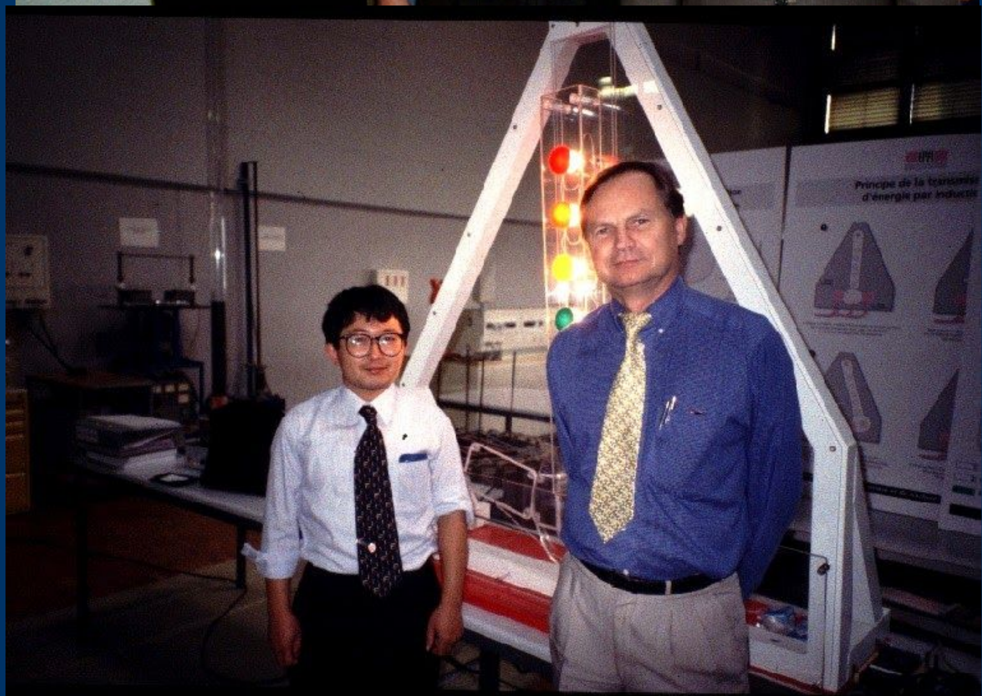
Zusammenfassung - Executive Summary

内容要約版

Rolf Gutzwiller
Peter Scheidegger
Hans Schlunegger
Oskar Stalder

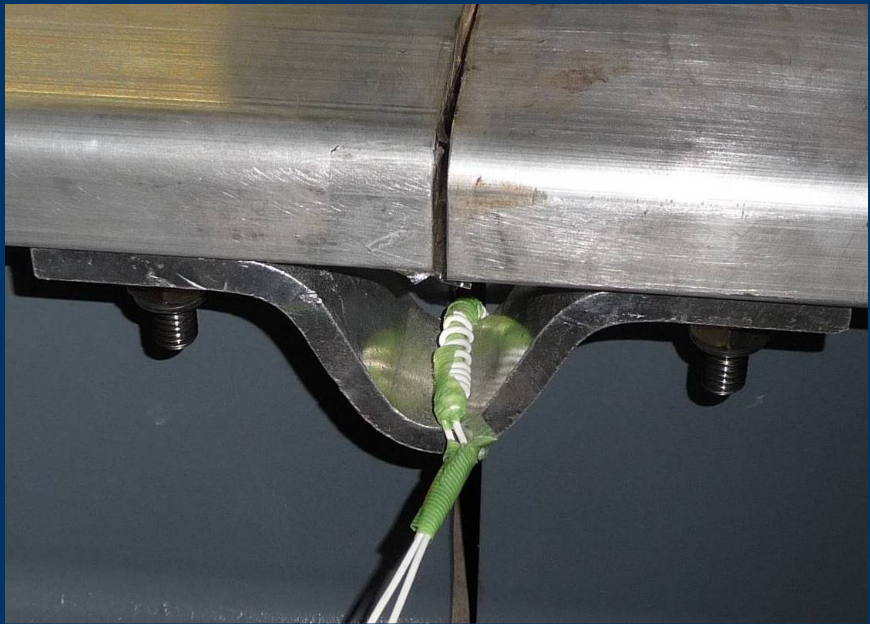
Februar 1997

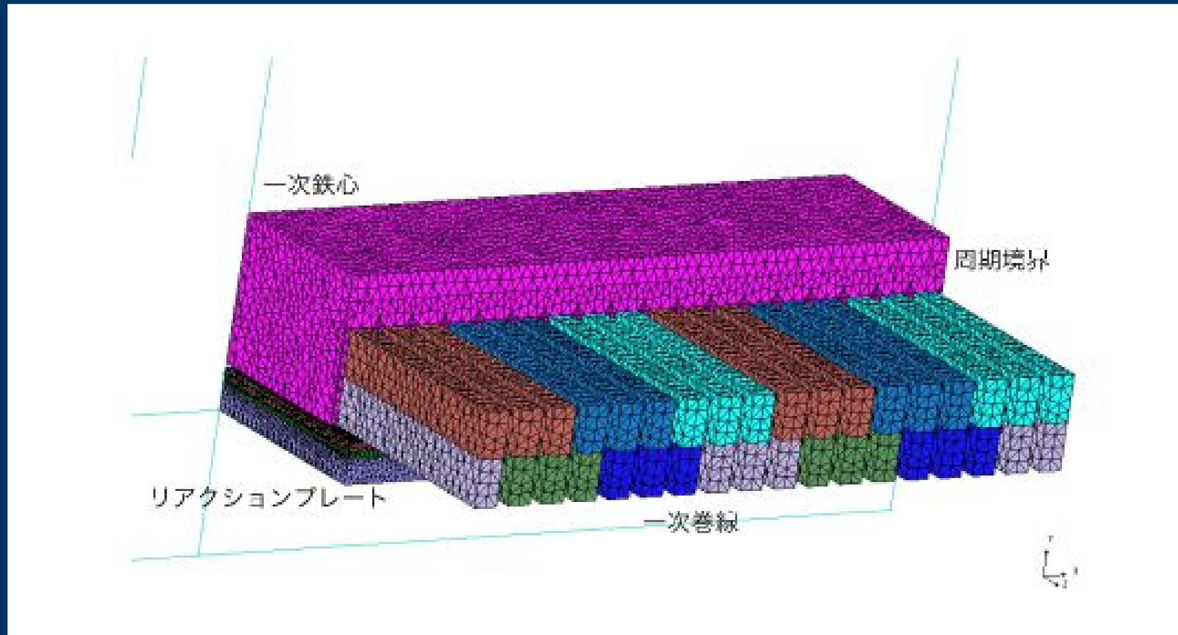
Swiss contacts 1996-2017

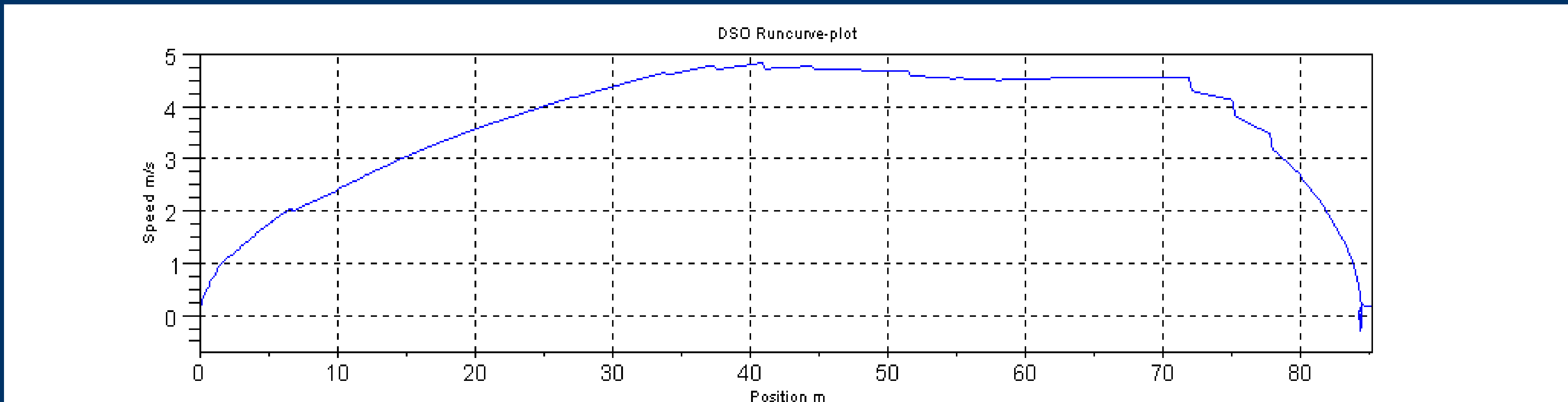


Recent activities

Linear Induction Motor







International standardization

Growing global markets:

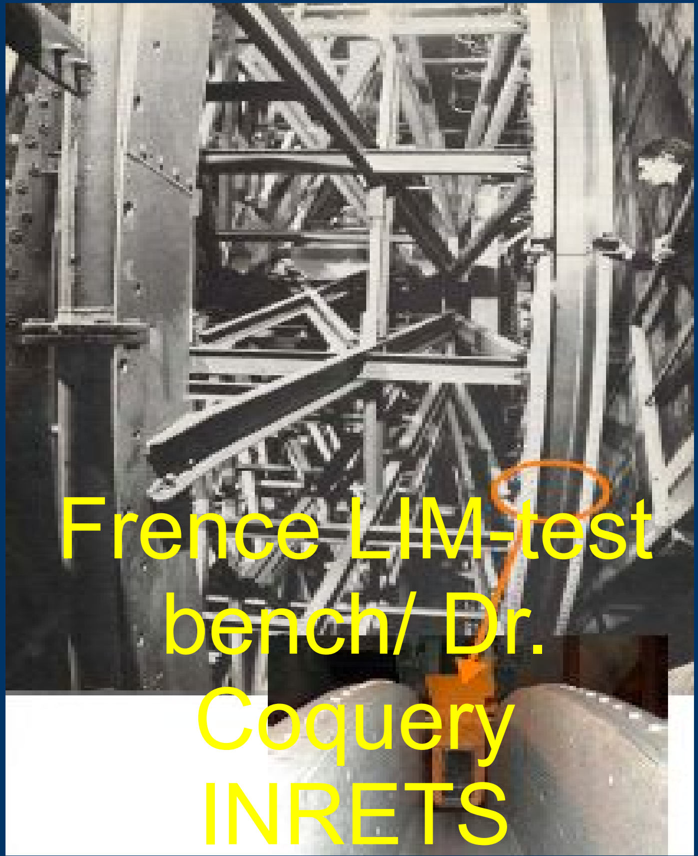
Effort of Bombardier
Korean studies,
Chinese studies,...

Canadian application in Vancouver

Necessity of International Technical Standard

Working schedule

1. The 1st project meting at Kyoto, Japan in January 2008
2. The 2nd project meeting at Kingston, Canada in December 2008
3. The 3rd project meeting at Versaille, France in January 2010.



Working documents and votes

PROJECT SCHEDULE

Stage	Document	Date	Target Date
PNW	9/1017/NP	19 January 2007	
ANW	9/1056/RVN	25 May 2007	15 June 2007
1CD	9/1161/CD	11 July 2008	30 June 2008
CDM	9/1209/CC	31 October 2008	30 November 2008
ACDV	9/1209/CC	7 November 2008	31 December 2008
CCDV	9/1269/CDV	29 May 2009	30 June 2009
ADIS	9/1372/RVC	22 January 2010	31 January 2010
DEC		22 December 2010	30 September 2010
RDIS		12 January 2011	15 January 2011
CDIS		31 March 2011	
APUB		**31 May 2011**	

Published in 2011

Publication: IEC-62520

62520 © IEC:2011 – 7 –

RAILWAY APPLICATIONS –
ELECTRIC TRACTION –
SHORT-PRIMARY TYPE LINEAR INDUCTION
MOTORS (LIM) FED BY POWER CONVERTERS

1 Scope

This International standard applies to short-primary type linear induction motors (LIM) for propelling rail and road vehicles.

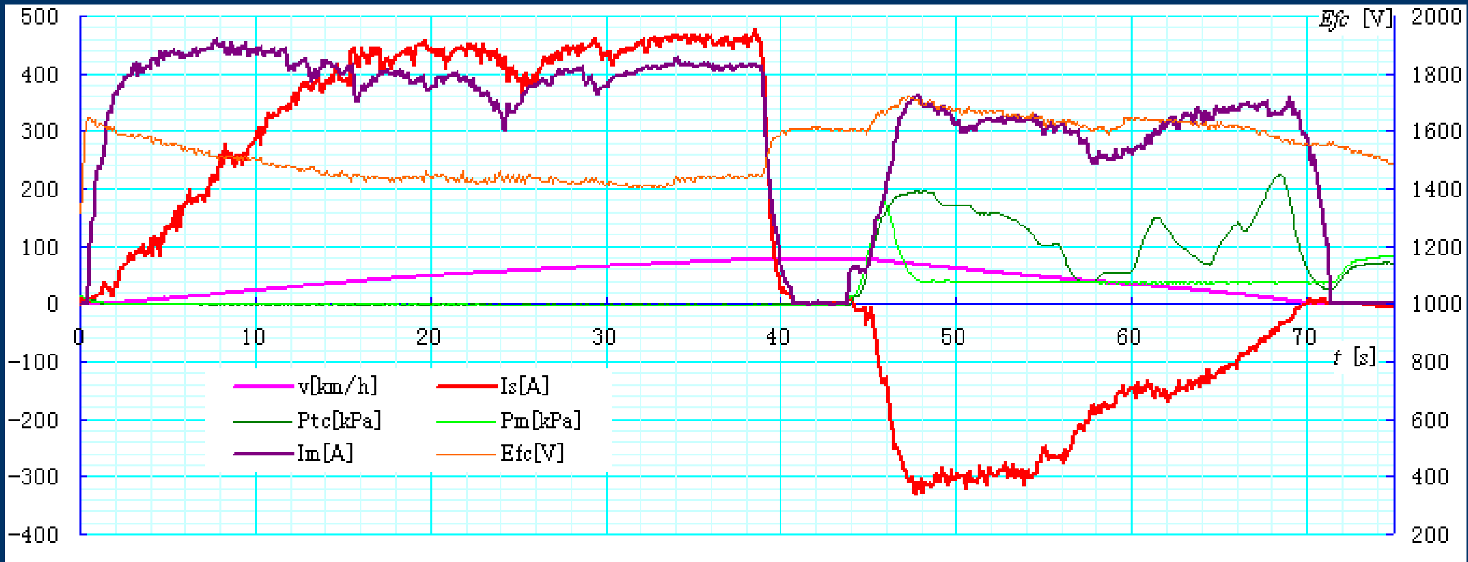
This standard applies to a specific configuration of LIM that has the primary mounted on either the vehicle body or trucks and a secondary that is fixed to the track and that is connected only by a magnetic field with the primary.

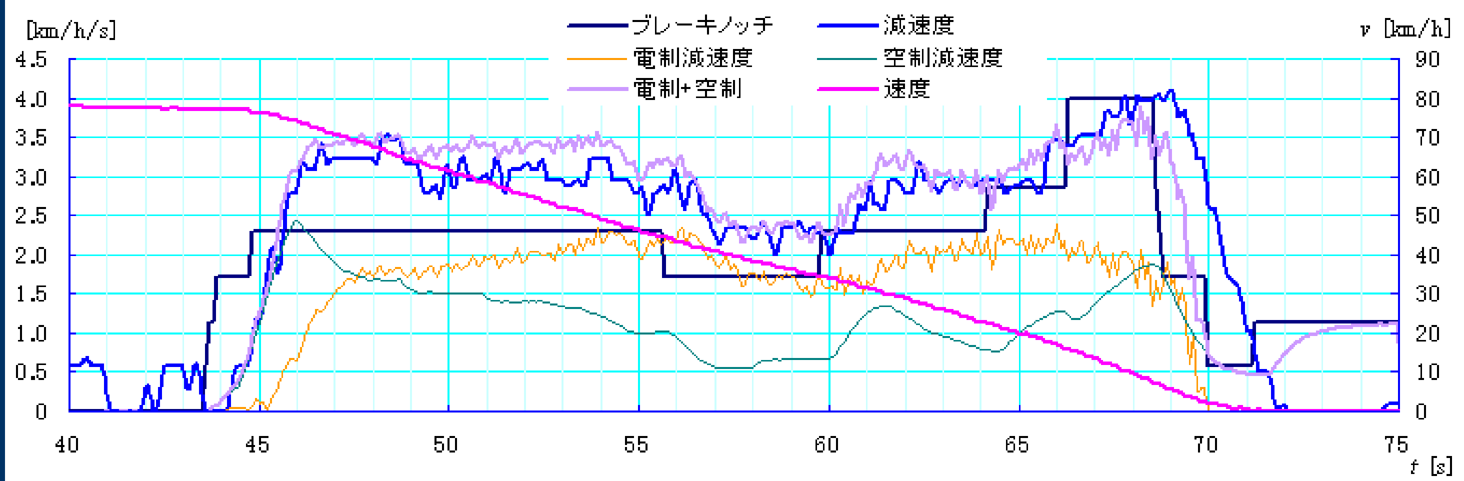
The object of this standard is to allow the performance of a LIM to be confirmed by tests and to provide a basis for assessment of its suitability for a specified duty.

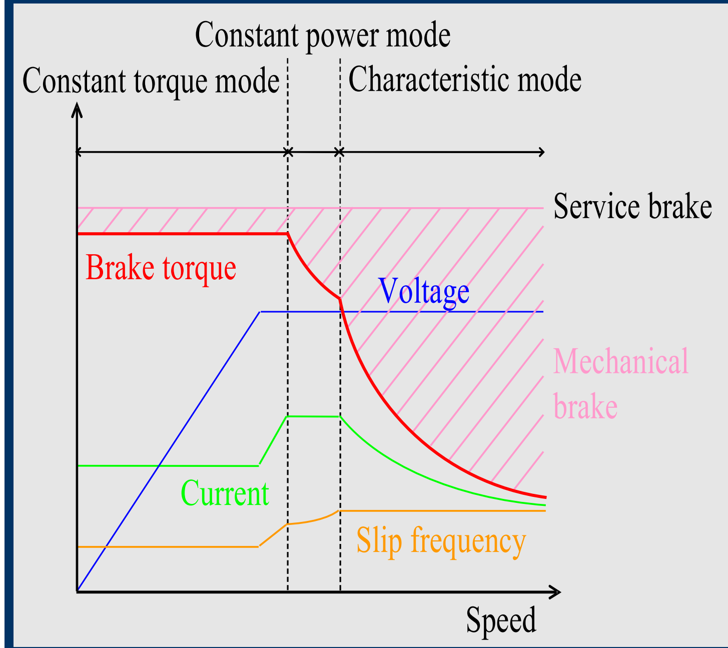
The rating of LIMs fed in parallel by a common converter should take into account the effect

Presently, I am a Japanese expert in **IEC/PT62888** for energy measurement.

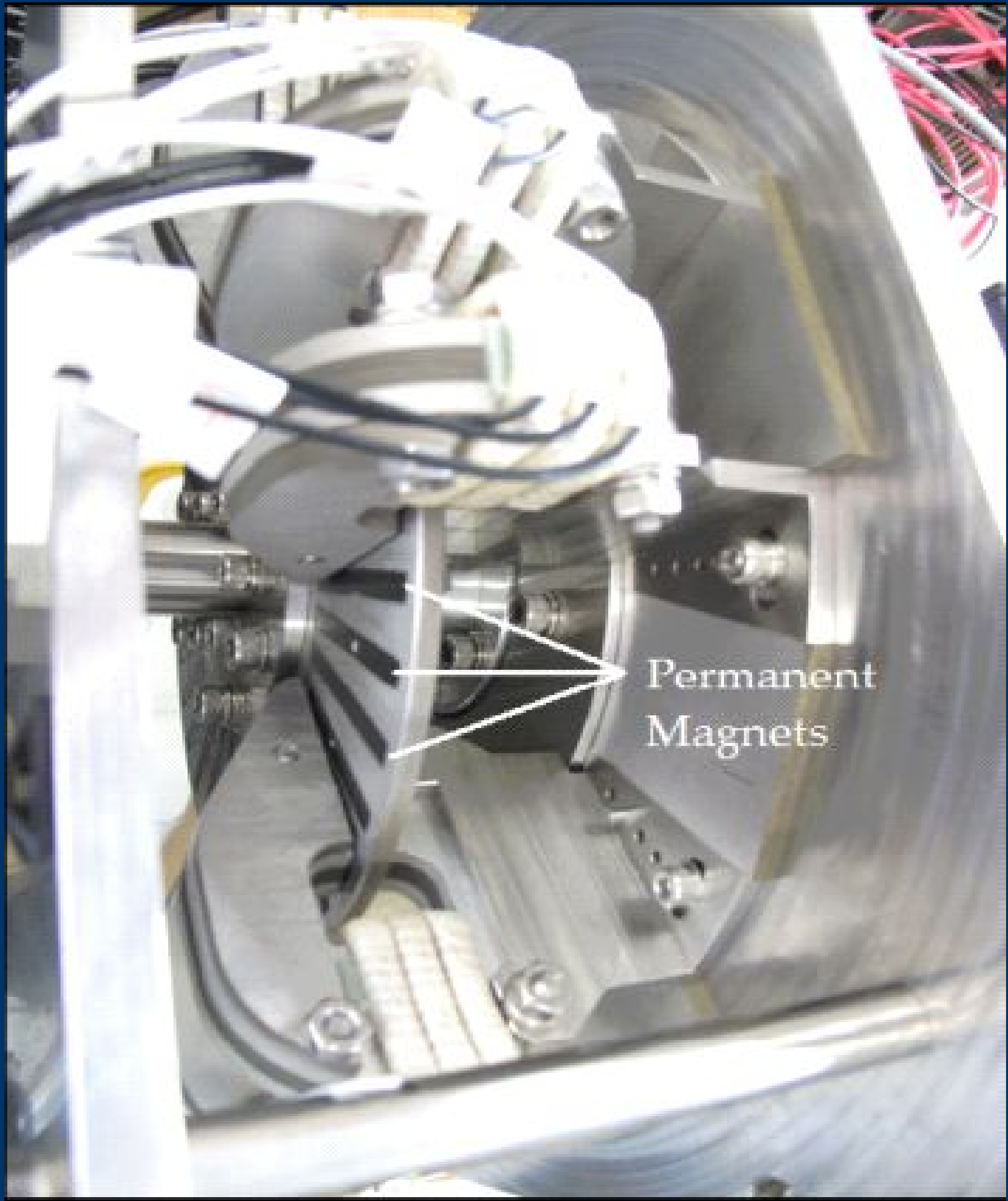
Power management and **regenerative brakes**



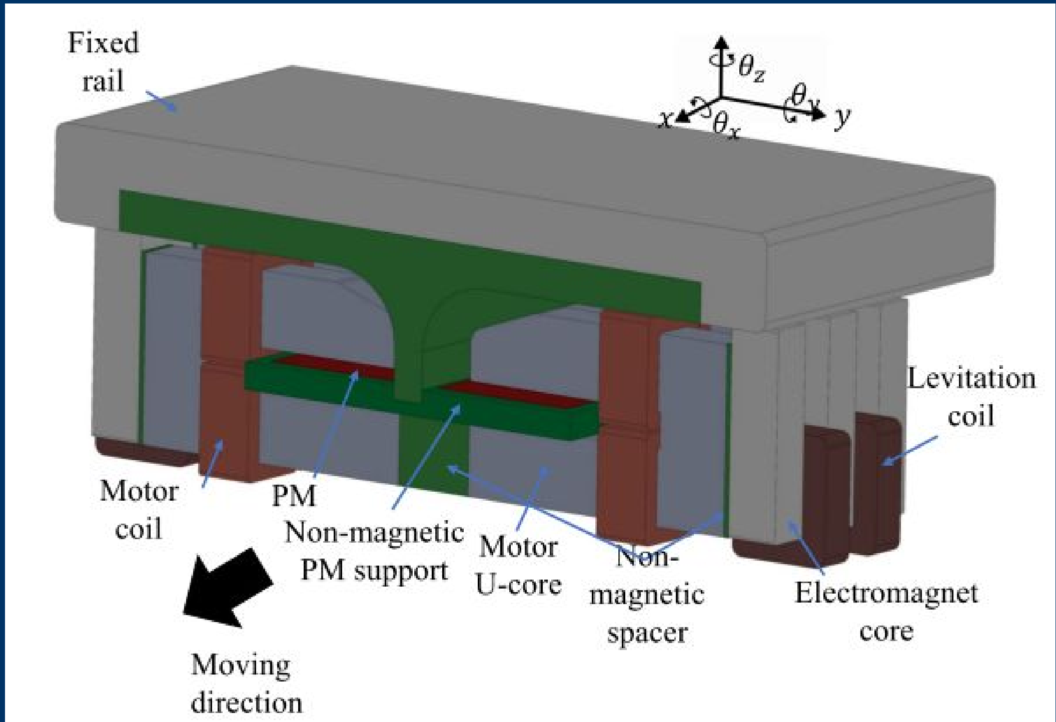


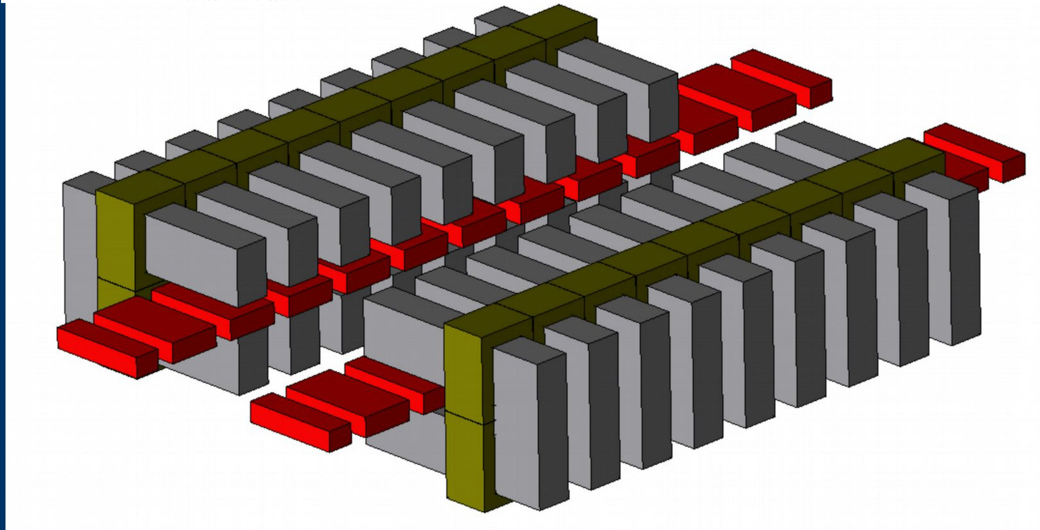


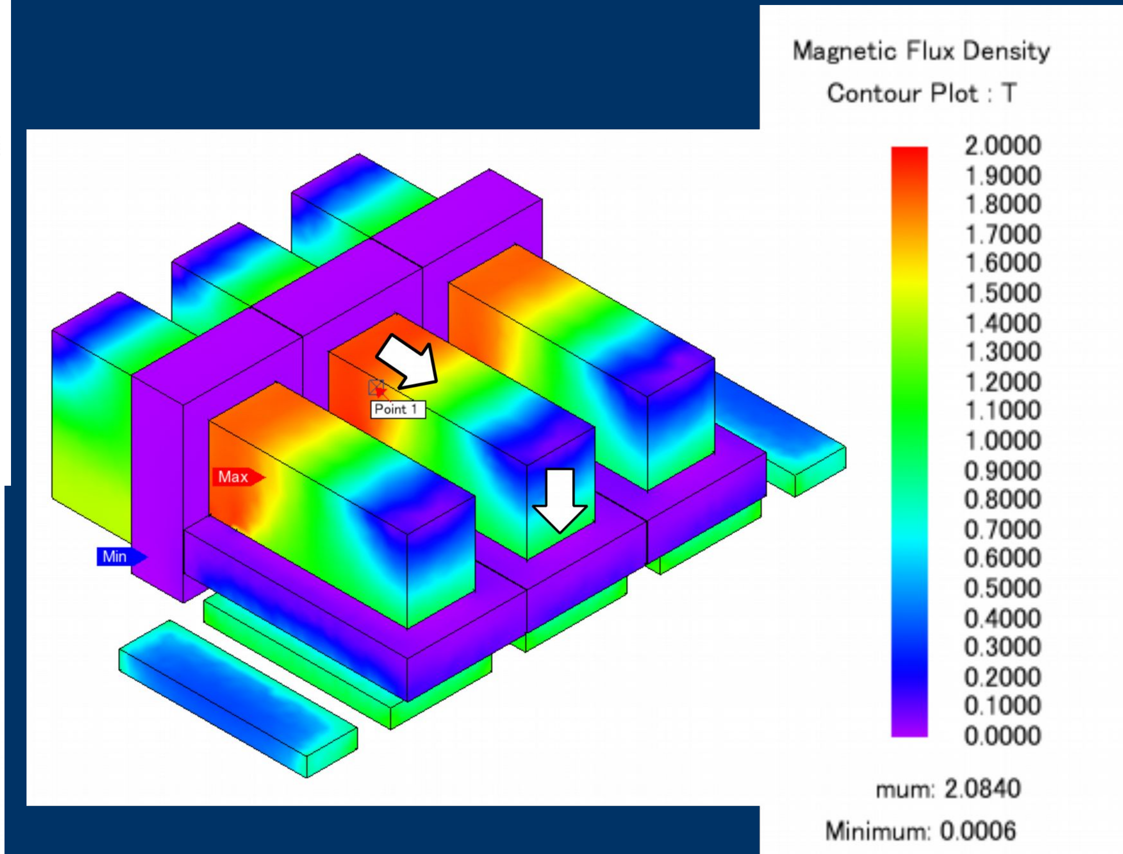
PMSM



PM-LSM & Maglev





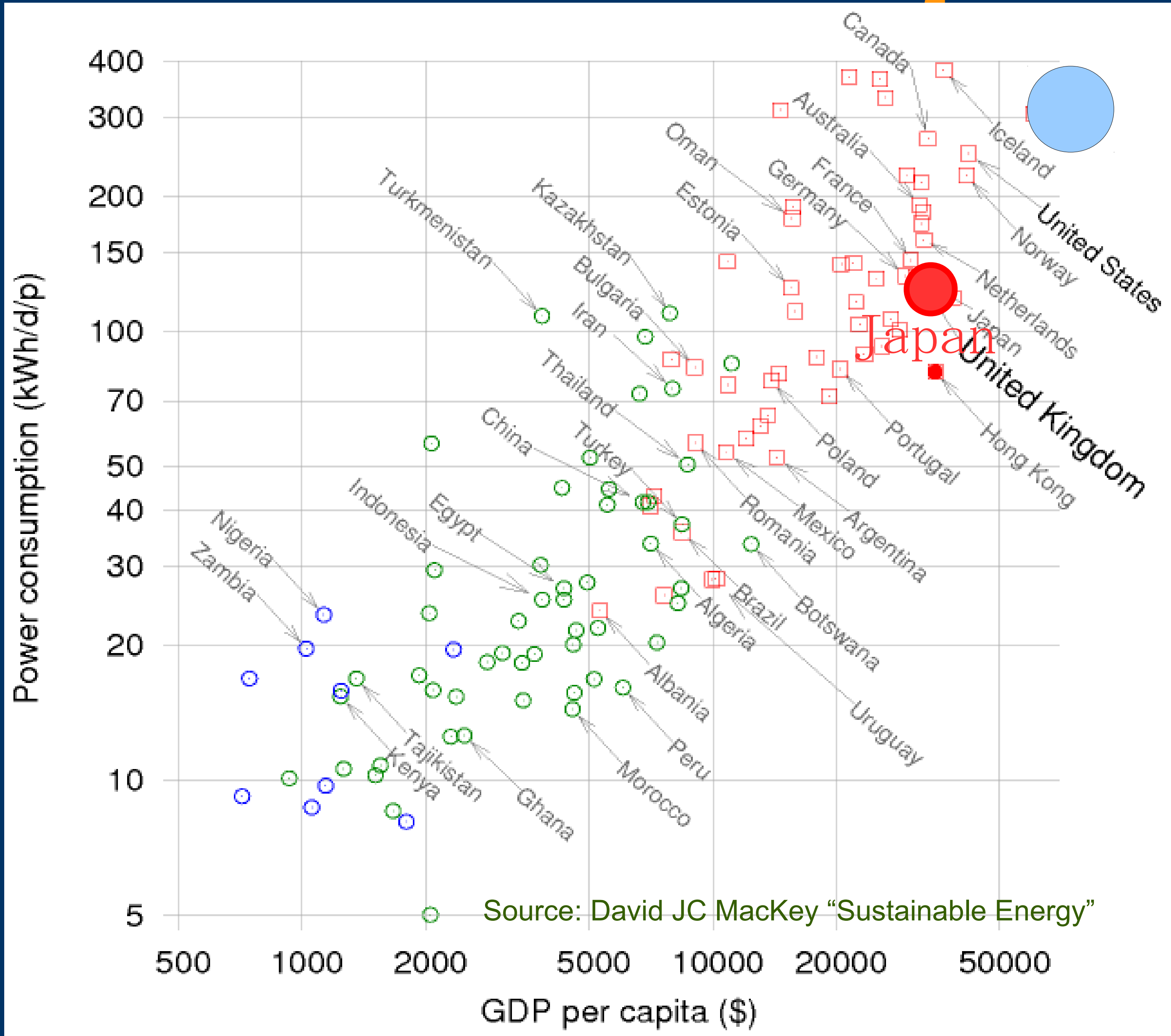


Koseki's laboratory 11th March 2011

Koseki's laboratory 11th March 2011

Koseki's route back to home in Tokyo on the 11th March 2011

Relationship between GDP & CO_2-emission



New motivation to save energy

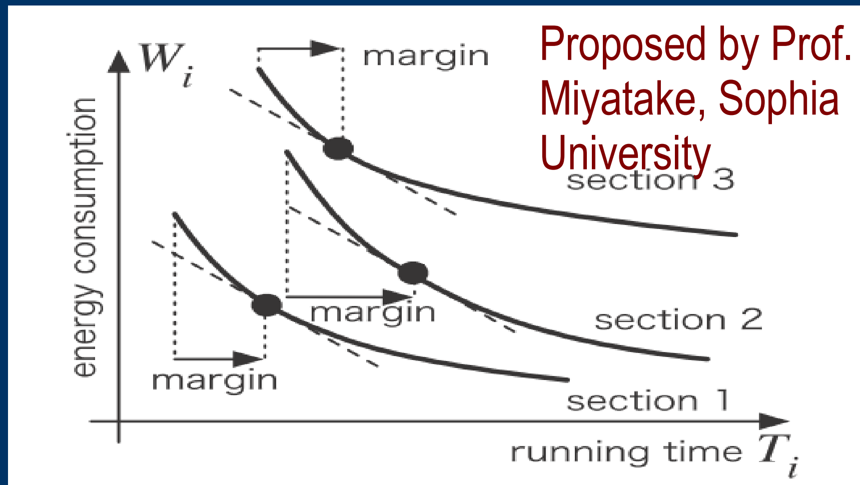
Social request after *11 March 2012 in Japan*

Energy-saving train operation

Modification of notch-off speed and brake-starting position
==> Considerable power/energy saving effects
by slightly longer traveling time

Reduced number of trains

Intentional modification of notch-off speed and brake-starting position

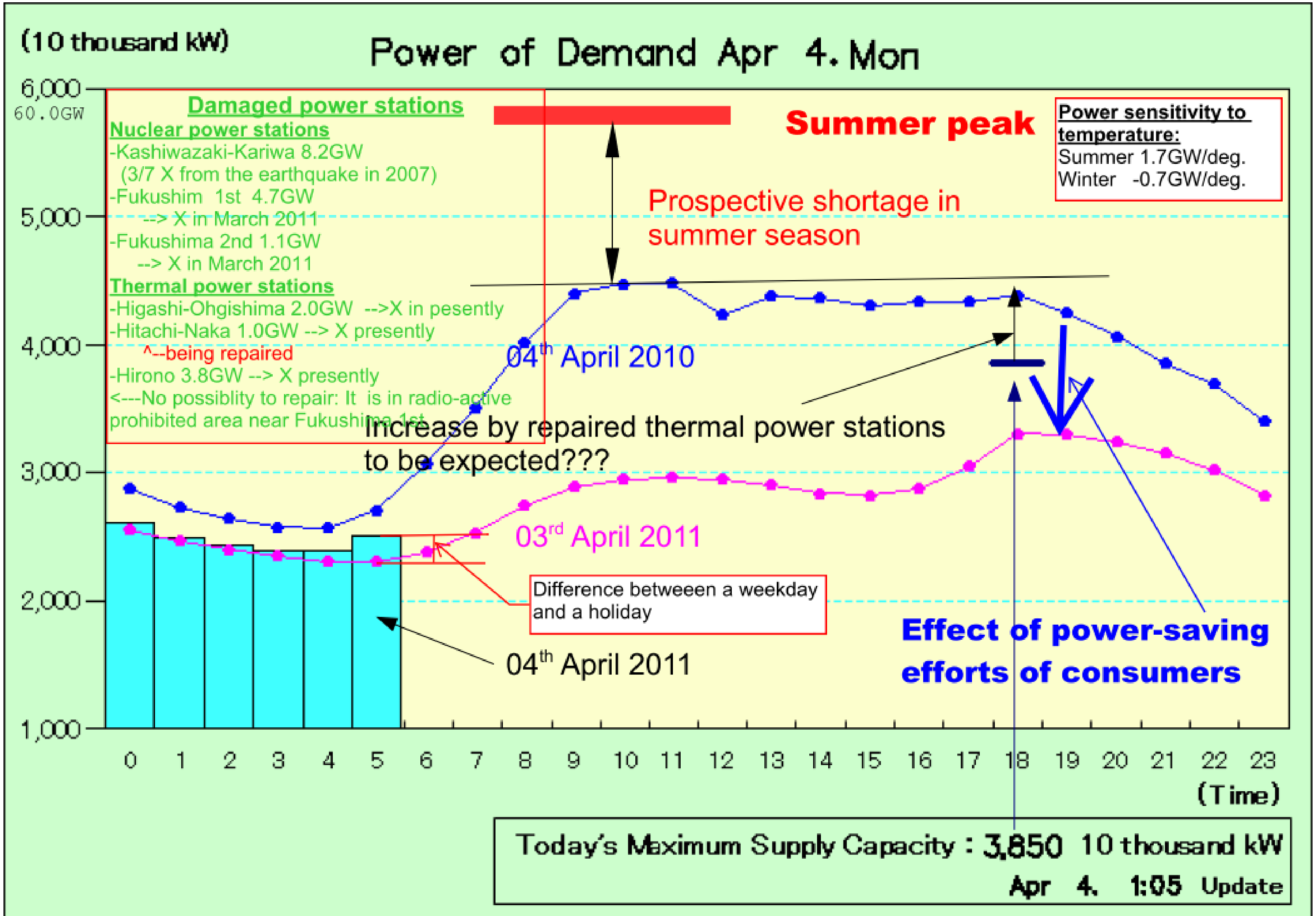


11th March 2011 (@Fukushima)

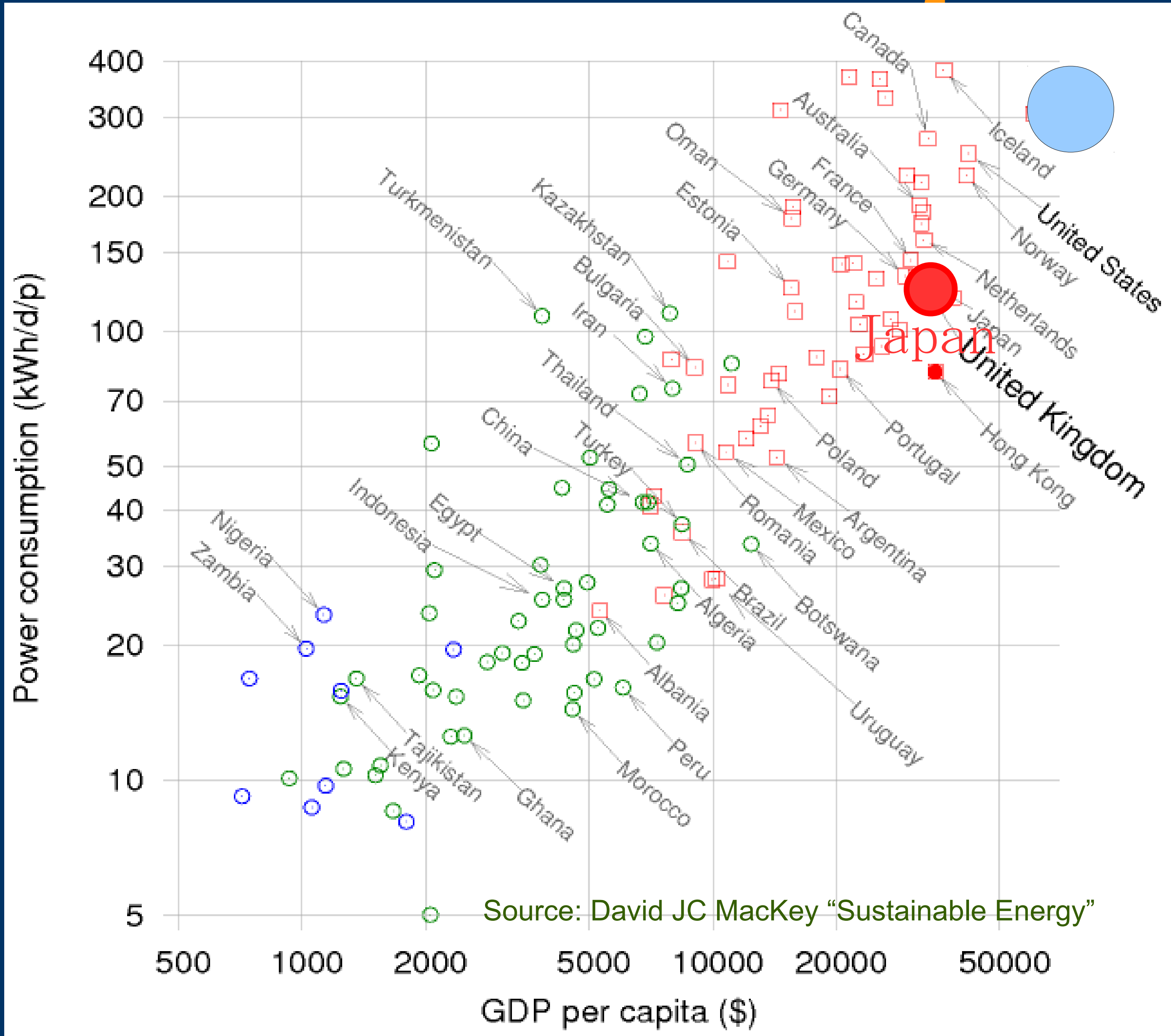
http://cryptome.org/ の記載から転載

Electric power supply after 3.11

See http://www.tepco.co.jp/en/forecast/html/index-e.html



Relationship between GDP & CO_2-emission



General introduction

Electric Railway in Japan

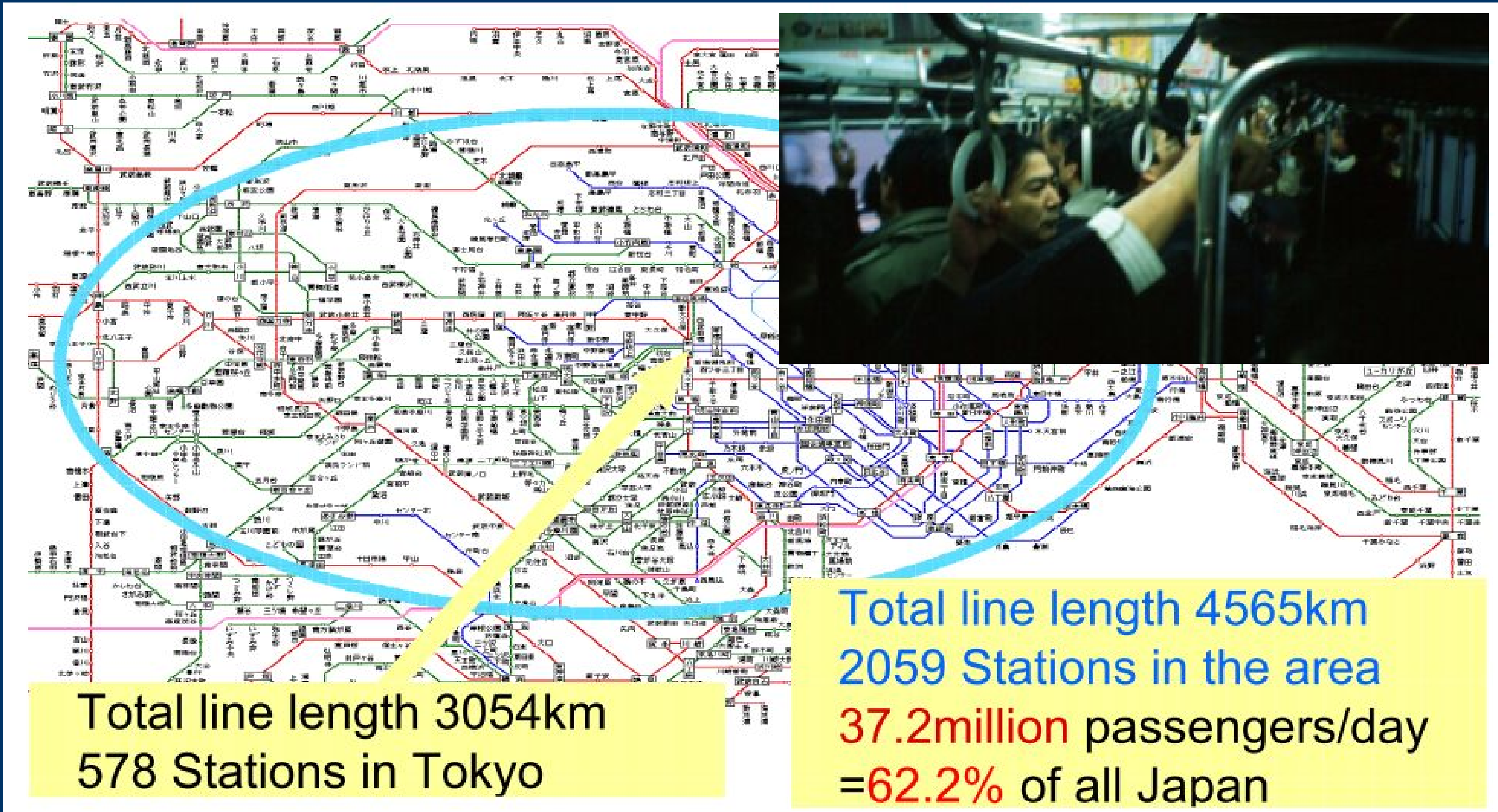
Introduction

Mobility and information technology:
Substitution or **inter-dependency**

Information technology is **essential infrastructure** for high-quality transportation systems

Speed/distance and the mode of the transportation
Significant role of **rail-guided public transports**

Large transportation market in Tokyo area



Total line length 3054km
578 Stations in Tokyo

Total line length 4565km
2059 Stations in the area
37.2million passengers/day
=62.2% of all Japan

Railway as a mass ground transportation

Most frequent operation in a morning peak hour

Chiyoda Line　Kitasenju

Weekday morning　8-9 o'clock　23 trains

Chuo Line Shinjuku　22 trains

Comparison of transport capacity：

Commuter heavy rail　approx. 140Passengers/car

e.g.,　Series E233　1539 passengers /10 cars

Shinkansen：Series 300 Nominal passenger number

Green car (2nd class?)　200 passengers

Normal car 1,123passengers　total 1,323passengers

Tokaido Shinkansen：　4.2x10^5 passengers /day

Compared to：

Bus 60-70passengers

LRT　approx. 70 passengers/car（approx. 20tos）

Nancy　TVR　145人　Translohr 110人

Jumbo jet747-400　420 passengers

(Fuel 21x10^{4}l、Cruising distance 13000km)

Electric engineer and rail guided-transportation

How about in safety?

Are rail-guided systems substantially safe?

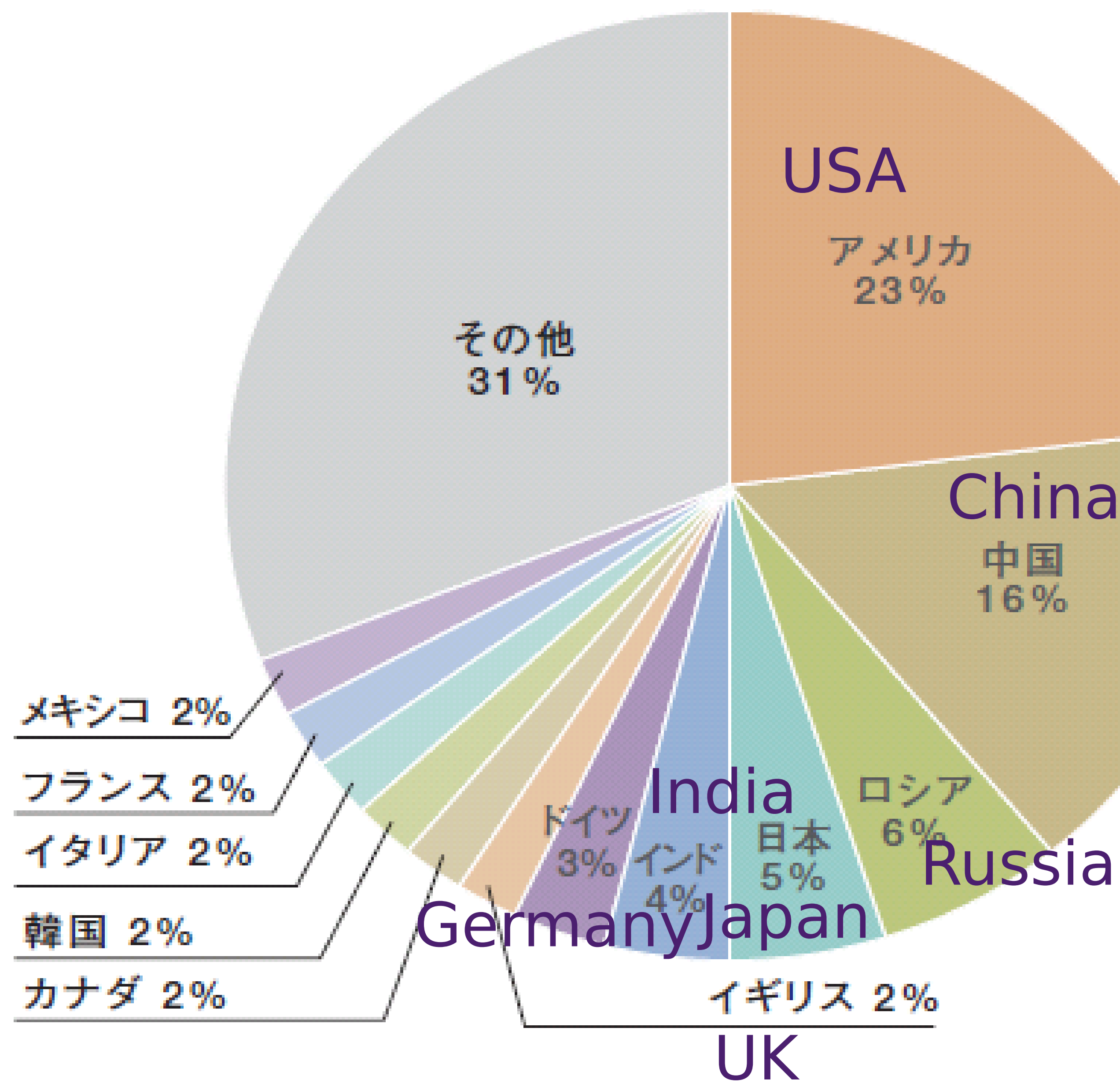
--> philosophy: fail safe system, machine backup

The role of rails cannot be justified solely by "Safety."

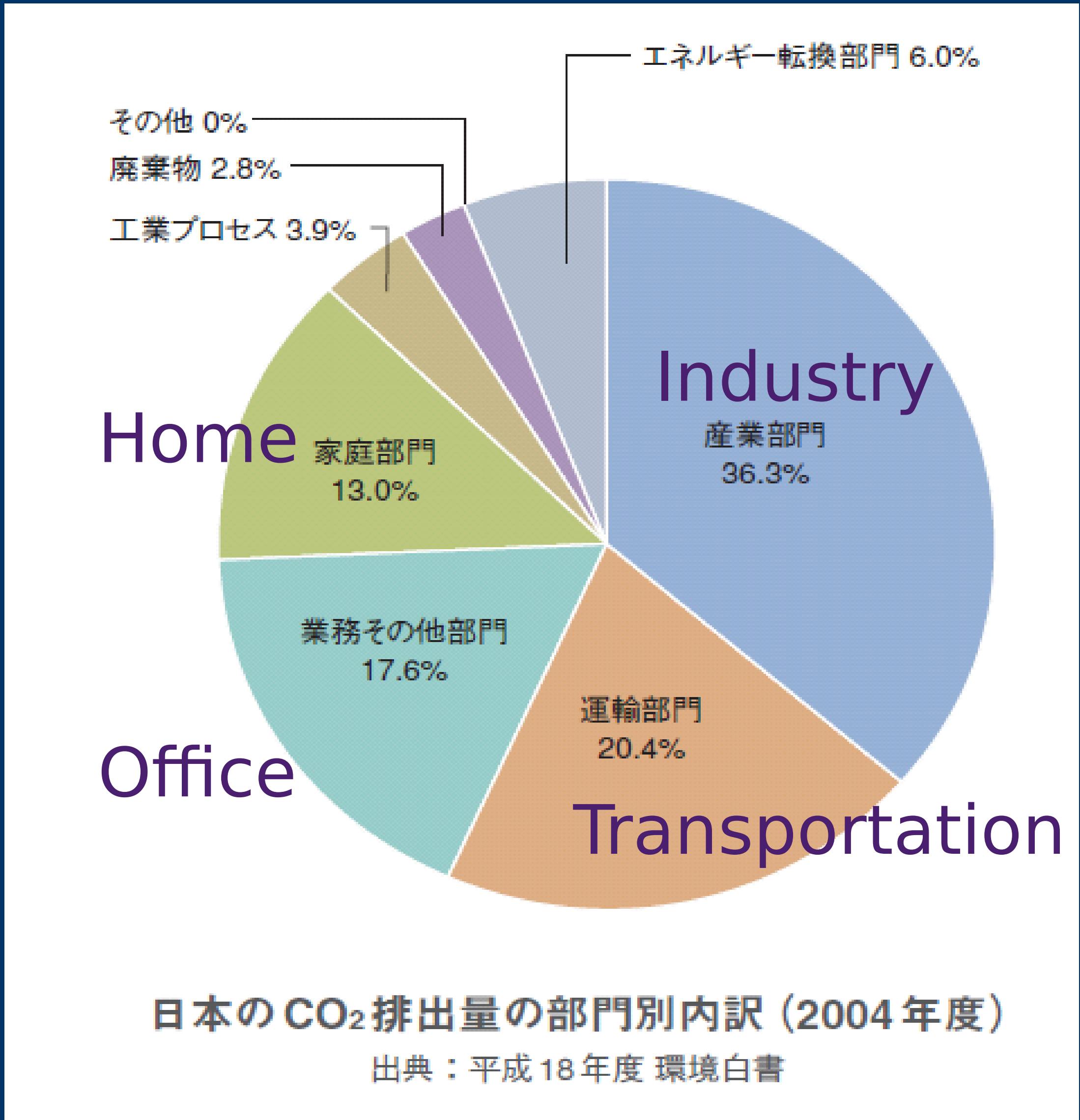
Recent trend: mitigation of the heavy load of safety system: trial in finding intermediate solution between rail and automobiles

Role of electrical and electronic engineers in railway operation ==> automatic operation, energy-saving

CO2 emission & Japan

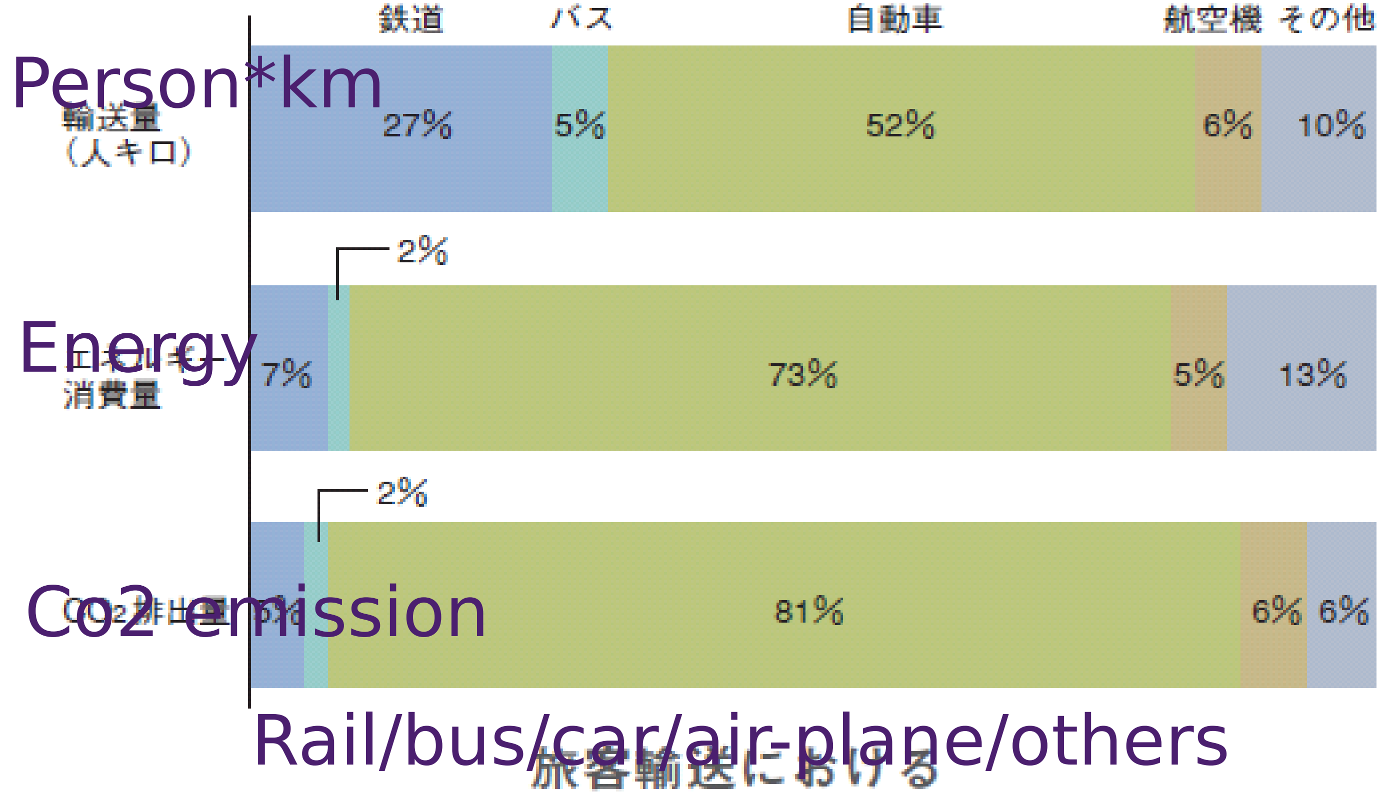


Transportation and environment



Transportation as 20% share of a CO_2 emission in Japan.

Relative transportation volume and energy consumption



旅客輸送における

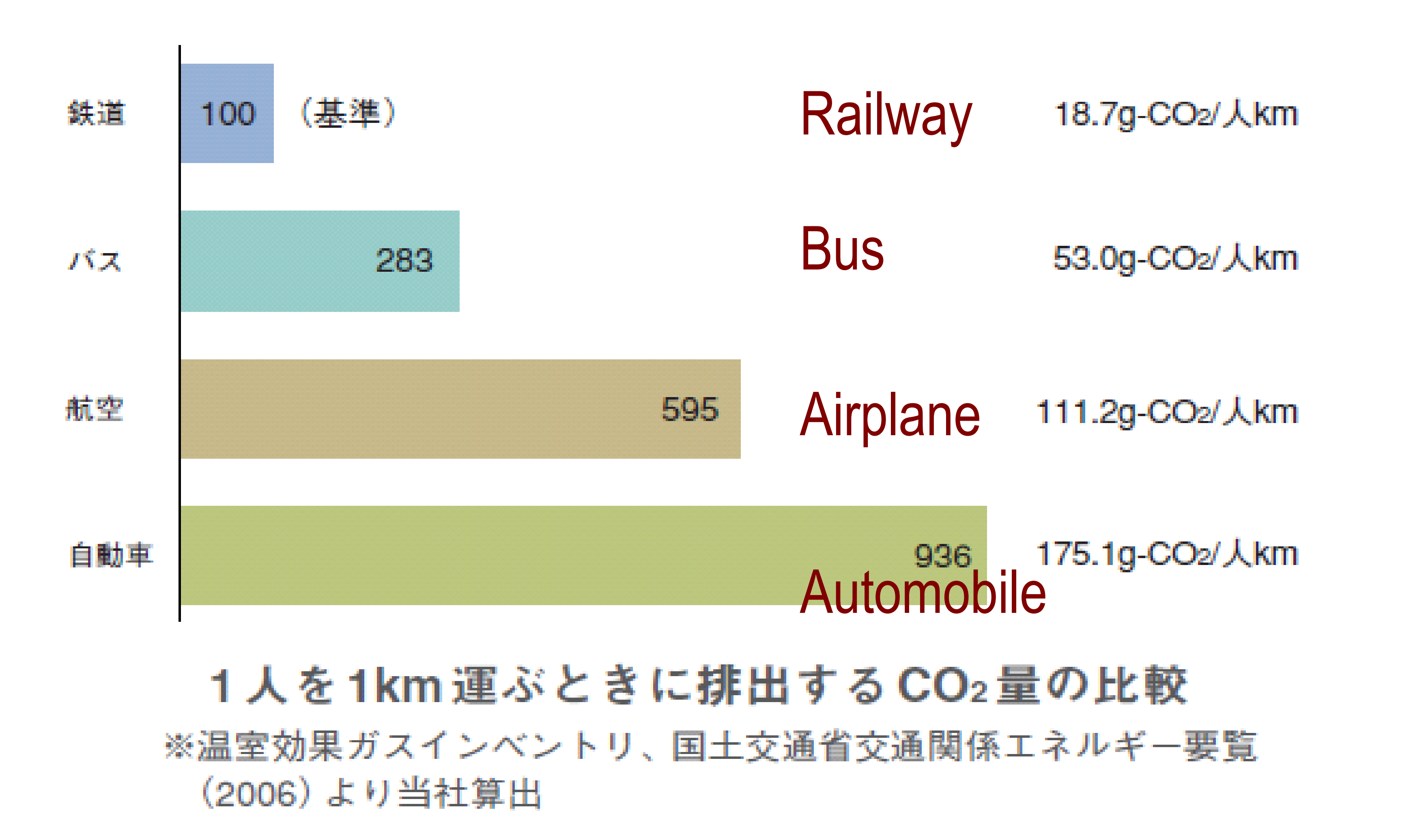
輸送量・エネルギー消費量・CO_2排出量分担率（2004年度）

出典：国土交通省交通関係エネルギー要覧（2006）

温室効果ガスインベントリ

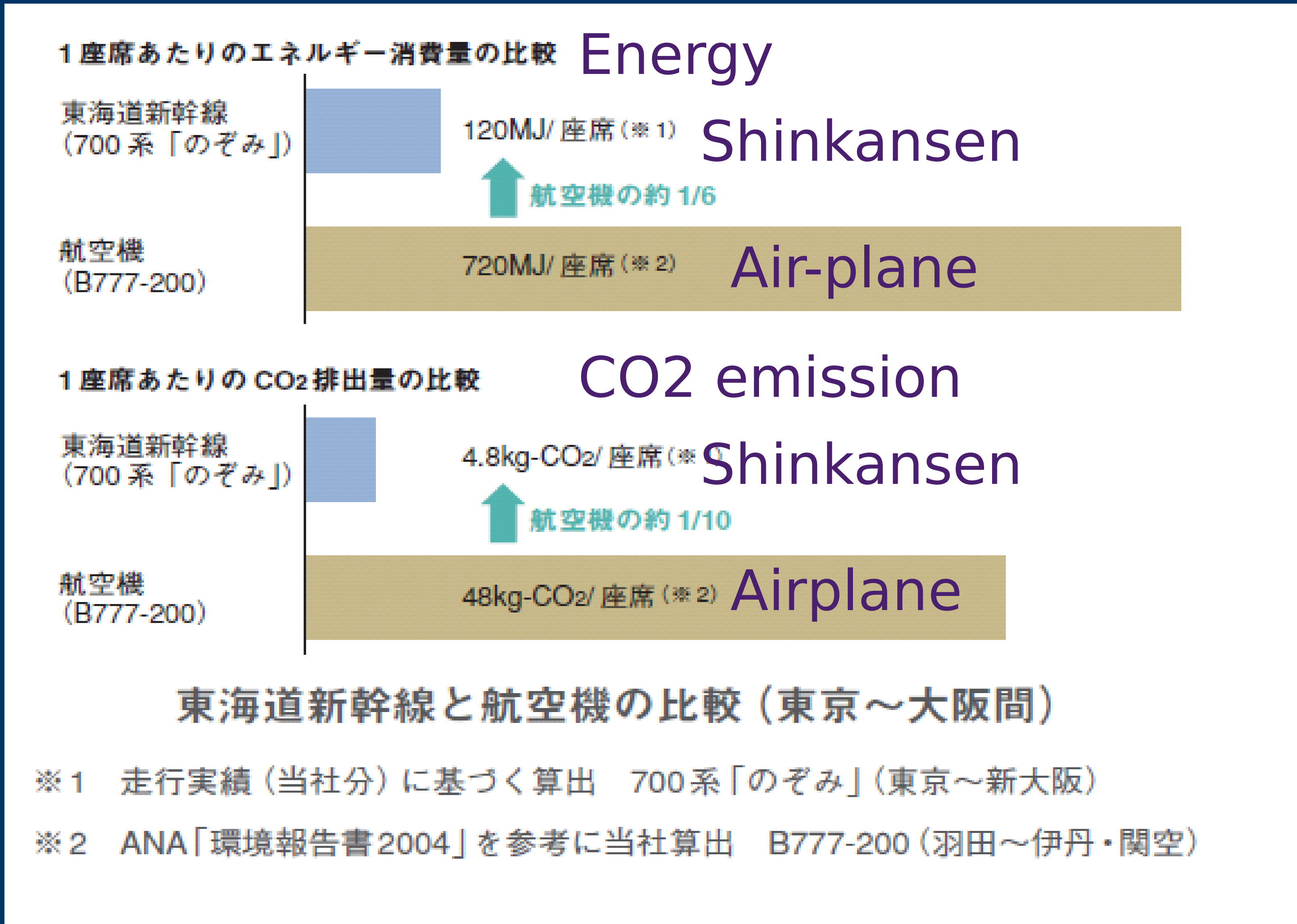
Relative transportation-km volume and energy consumption in passenger transport in 2006

Transportation mode and CO_2 emission



CO2 emmision needed to transport one person in 1km.

Comparison between Shinkan-Sen & Air plane



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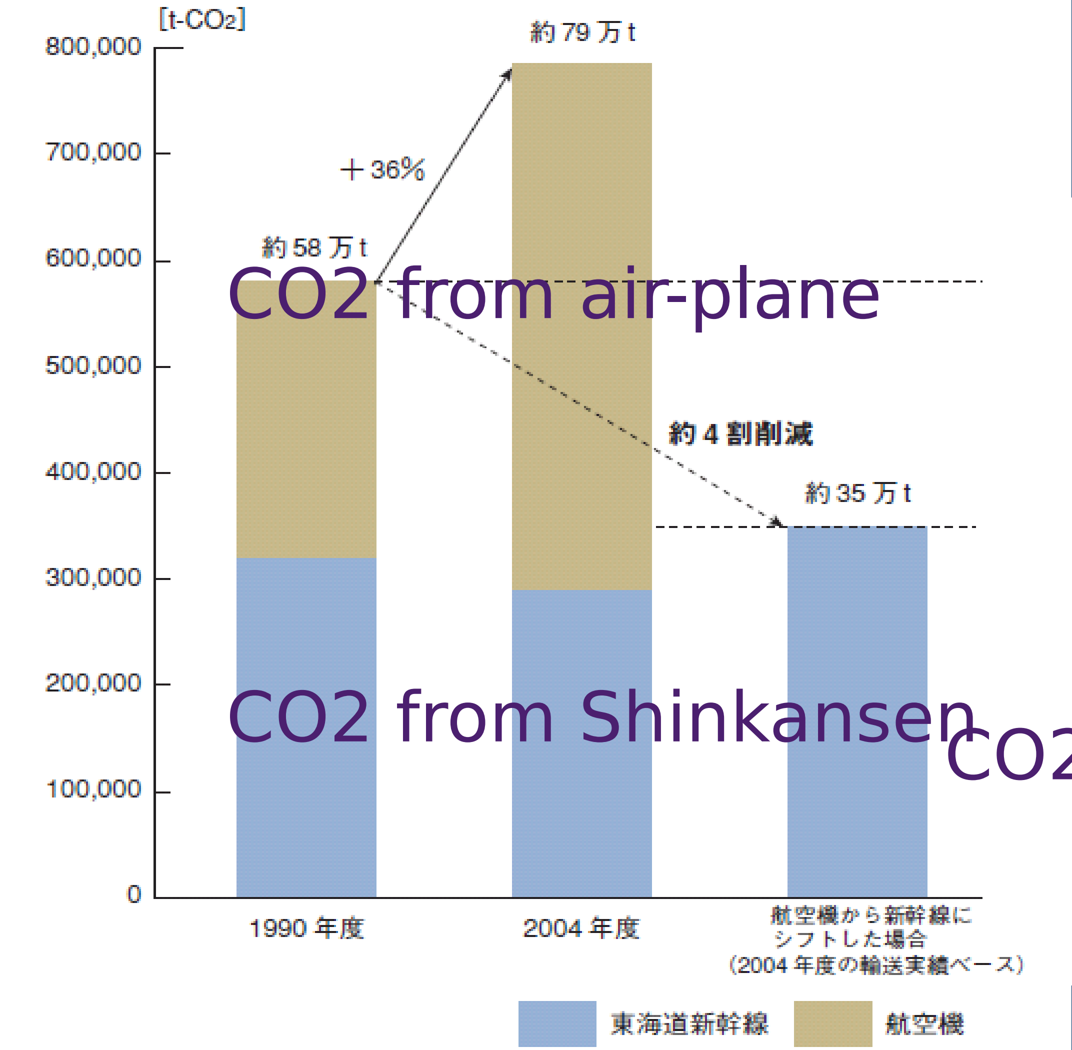
Comparison between Shinkan-Sen & Air plane



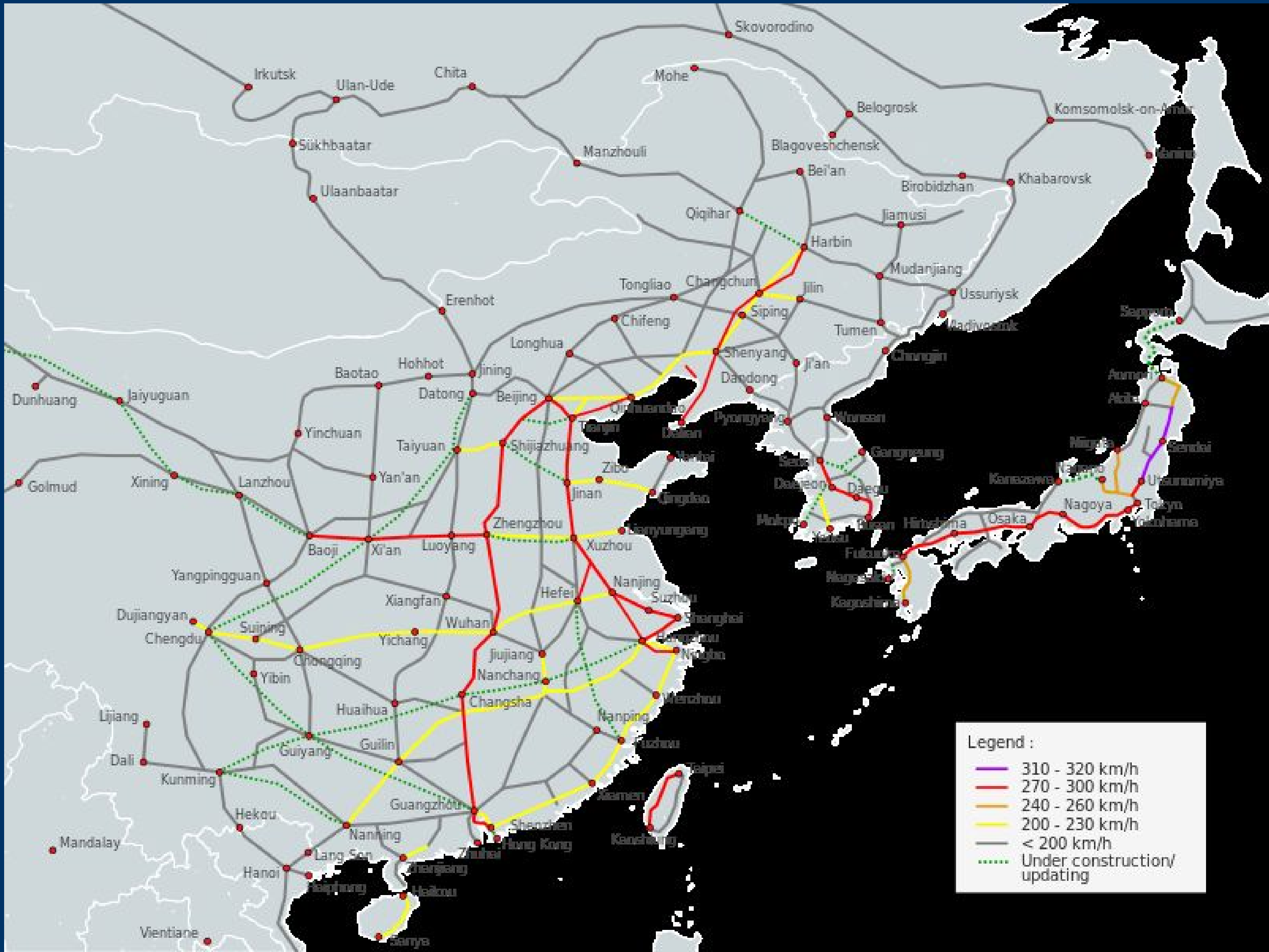
航空機から新幹線への旅客シフトによる CO₂排出量の削減効果（1990 年度比）

航空機から新幹線への旅客シフトによる CO₂排出量の削減効果（年間）

Advertizement of JR-Central

Electric power supply to trains

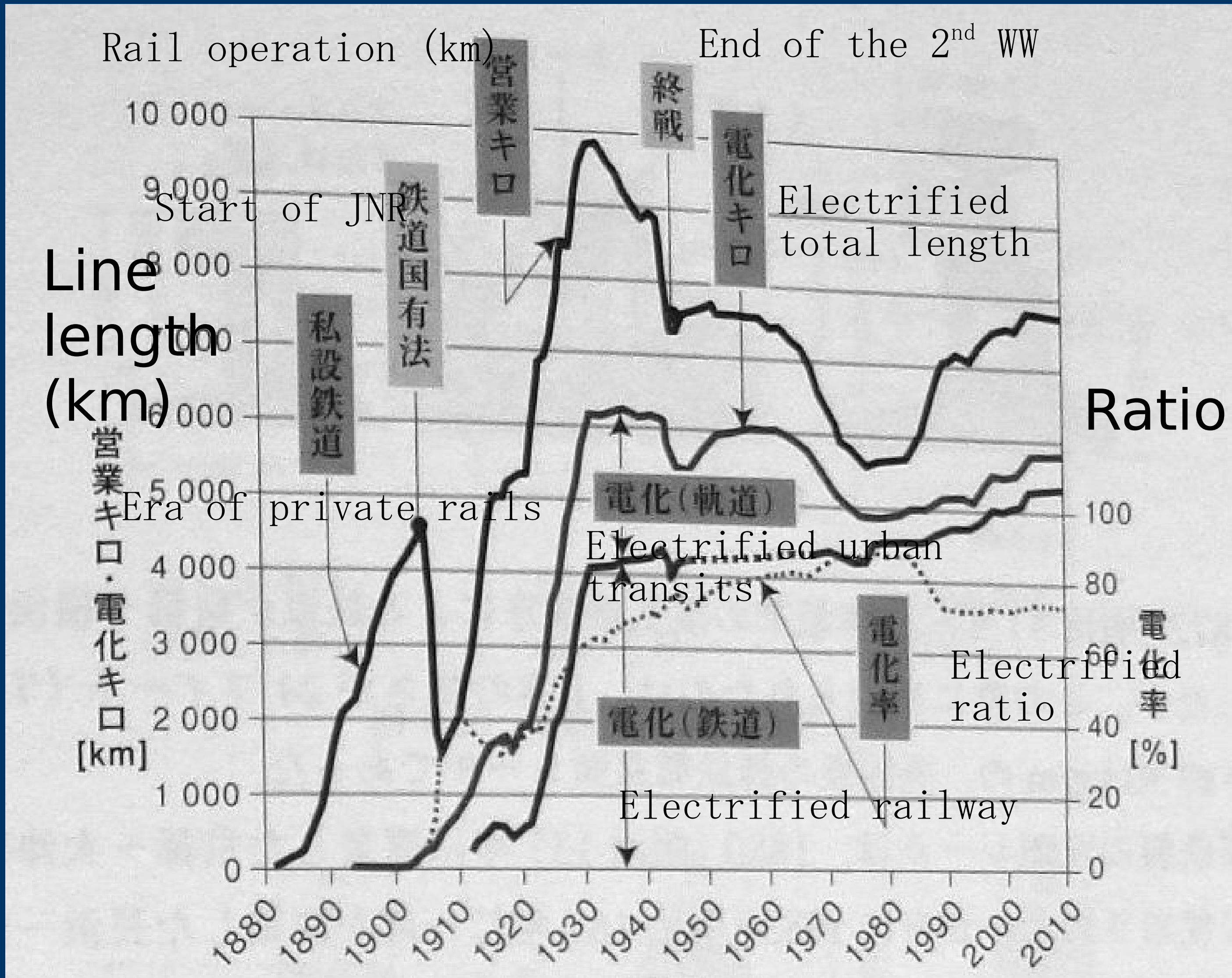
Rails in eastern Asia



Source: Wikipedia-Schnellfahrstrecke

Electrification in Japan

Conventional lines 9752km(2010 55.5%)
Shinkansen 2620km(2010 100%)



Electric rails in Japan

Electrification in JRs

- Conventional lines 9752km(2010 55.5%)
- Shinkansen 2620km(2010 100%)

DC electrification mainly for urban railways

AC electrification mainly **for intercity** railways

History of railway

Electric railway: small model of an electric vehicle with VOLTA's battery 1935

Industrial Exposition in Berlin in 1879 (W. Siemens)
3 trailer cars for 6 passengers DC 150V, 2.2kW, 2-pole DCM, 12km/h

1881
The first commercial passenger service by an electric train at Lichterfelde, Berlin, Germany

Electric rails in Japan

Wayside electric power supply

Powering

Regeneration

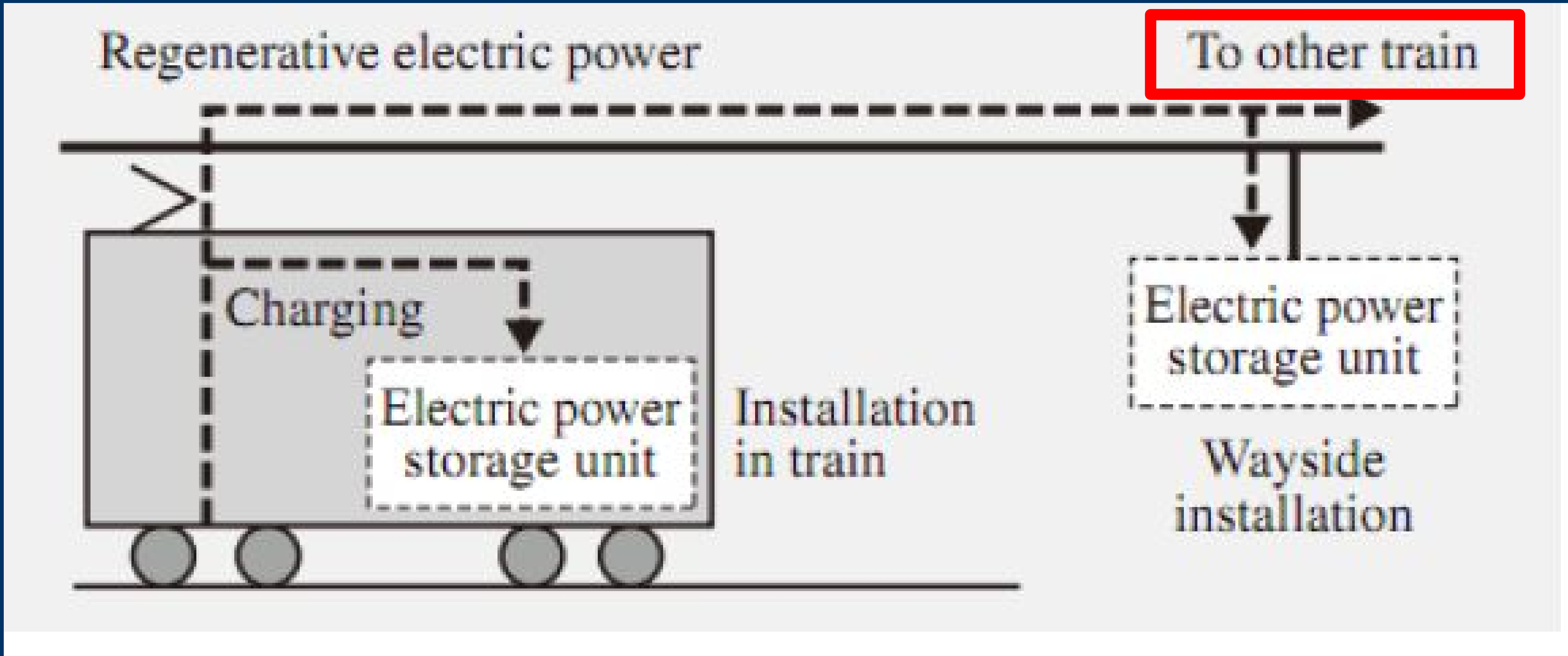
Electric trains

Research topic

Energy-saving train operation with the best use of regenerating brake under DC-electrified power network

2017/12/07

Regenerating brake and power flow



Braking operation and traction performance curve

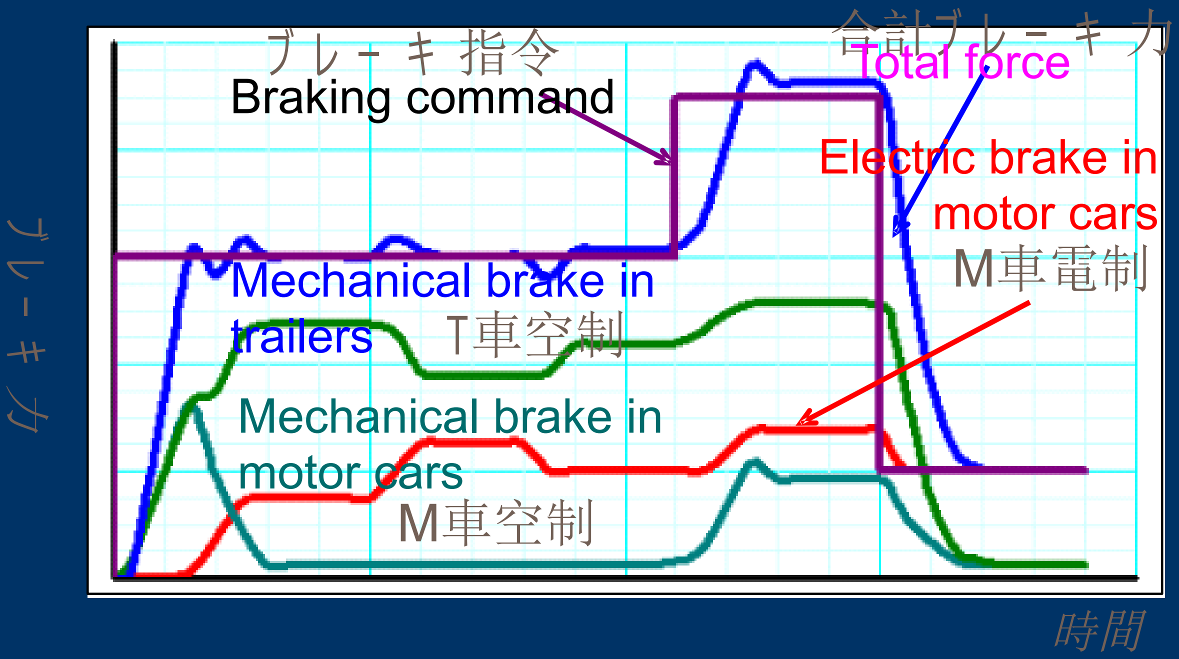
Traditional braking philosophy: Main: Mechanic/ Sub: Electric

=> **Pure Electric Braking** for ordinary operation

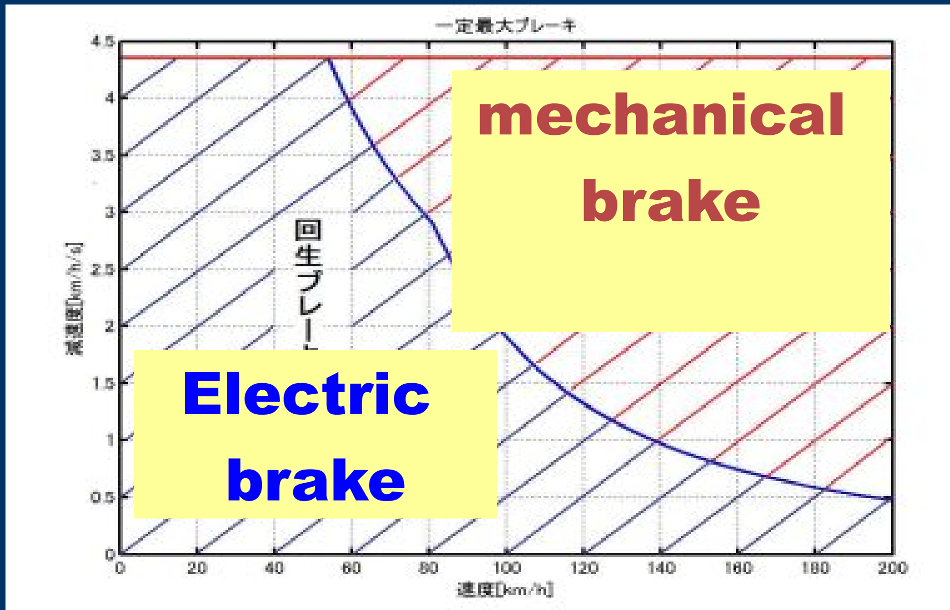
Supplemental mechanical brake in high speed: Conventional philosophy

Small braking force in high speed

==> Avoidance of cancellation of regeneration

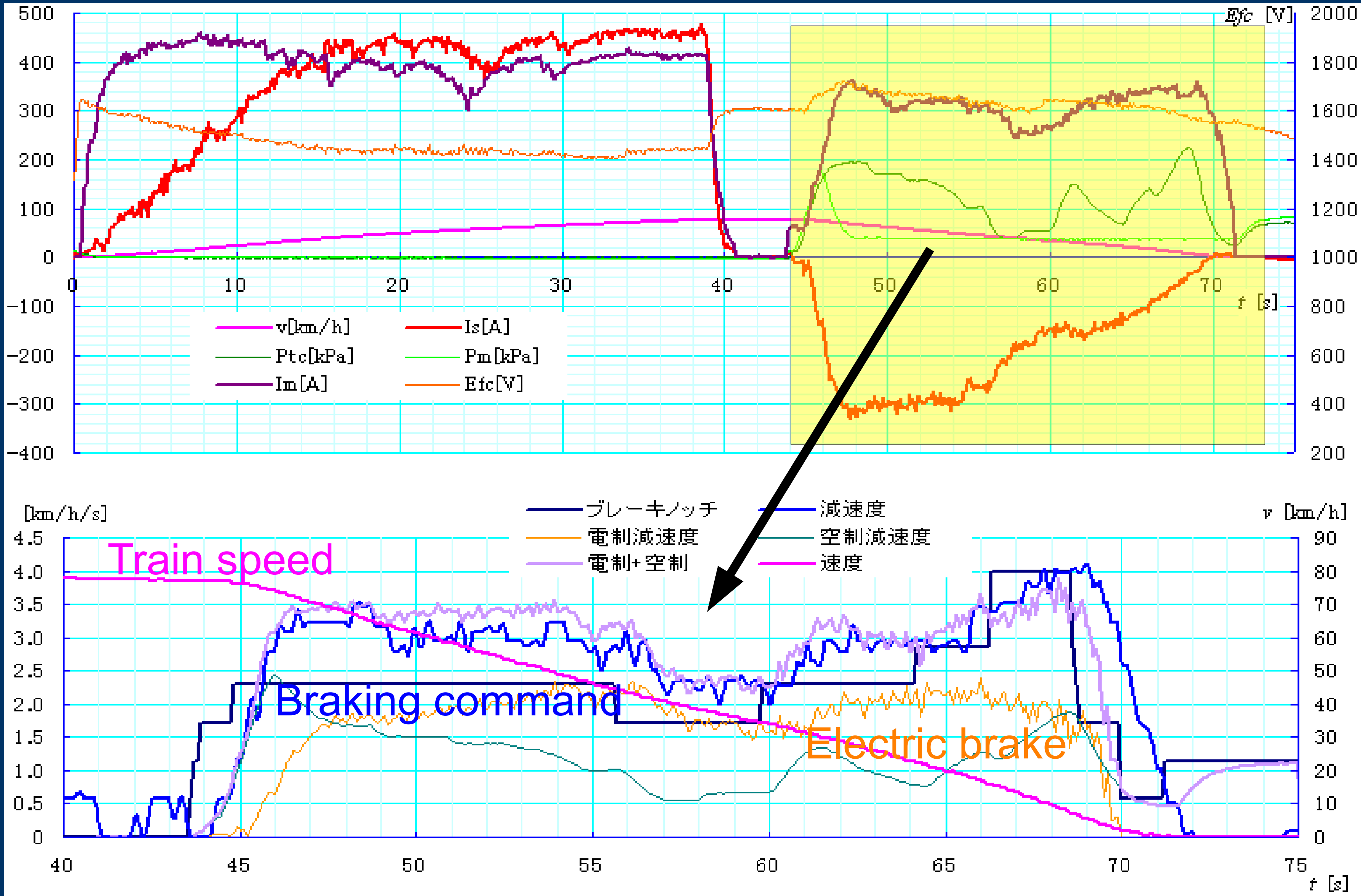


Conventional barking action



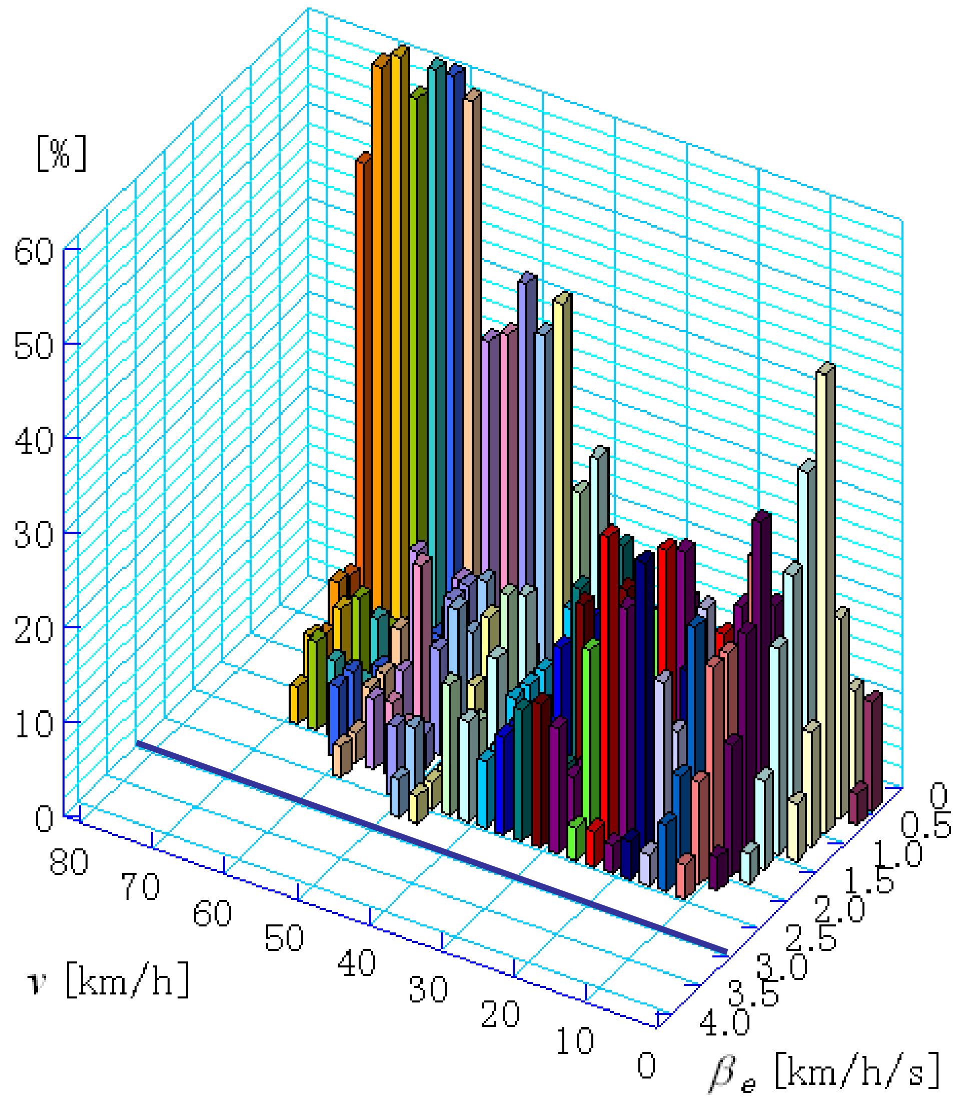
Speed and braking force

Early study in 1990's st Shin-Keisei

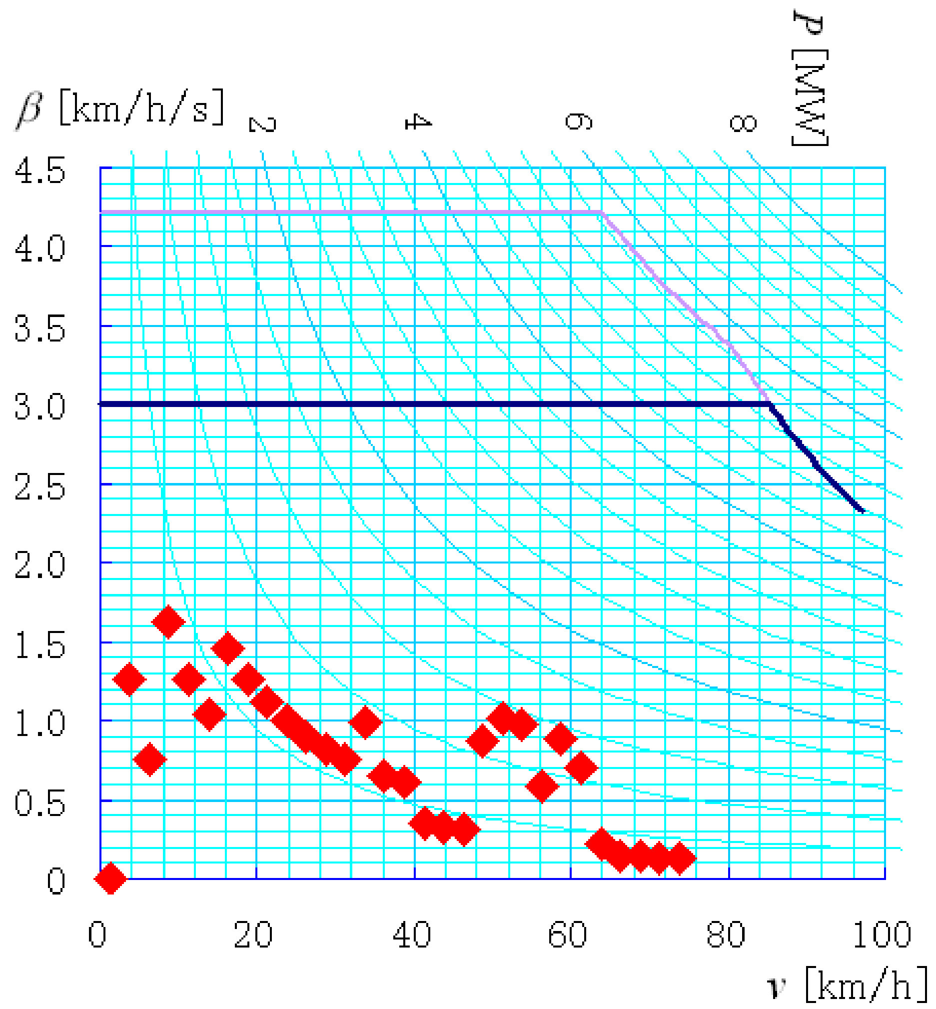


Early study in 1990's at Shin-Keisei

Measured contribution of regenerative brake



Probability of successful regenerative braking actions



Average contribution of regenerative braking actions

Strategies for avoiding cancellation of regenerative brakes

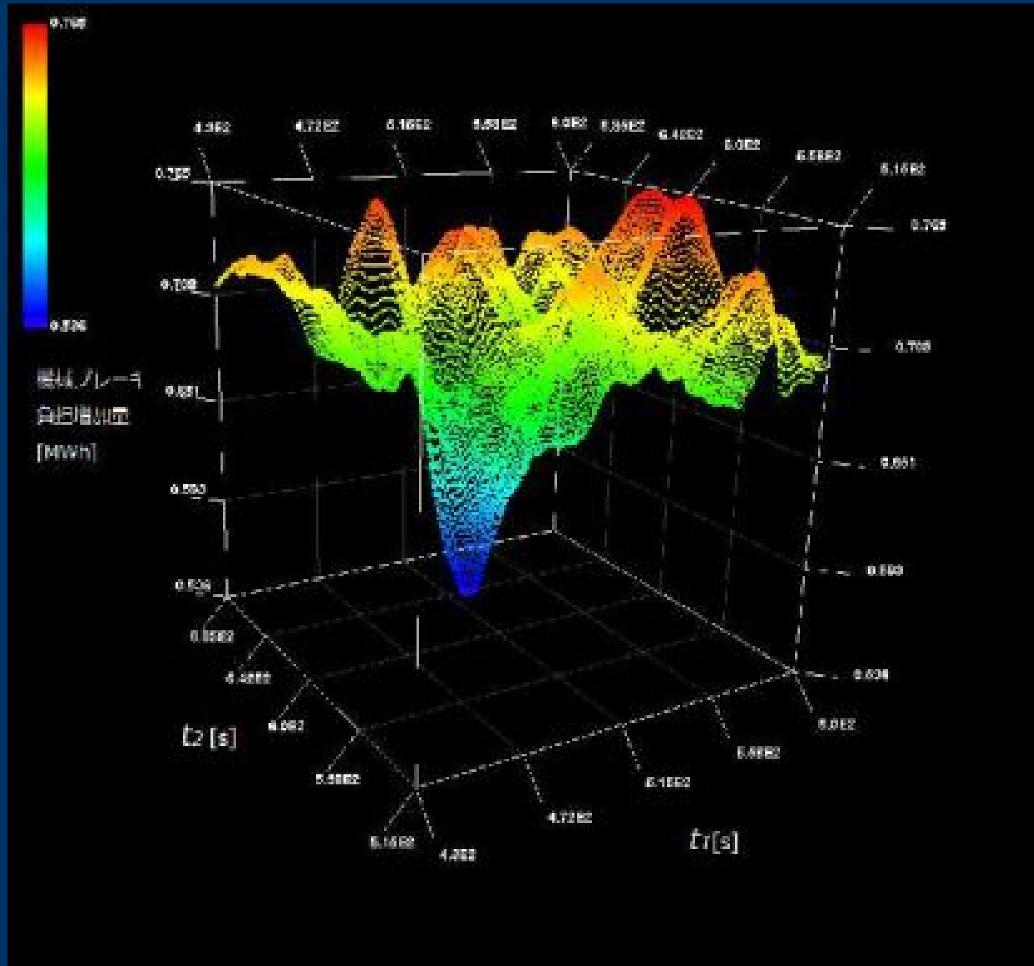
Regenerative substations

Onboard/Way-side energy storage devices

Tuning train intervals
Simultaneous acceleration/ deceleration

Appropriate converter control and protection at light load conditions

Avoidance of strong brake at high speed/ Improved train run-curve



Relationship between train interval and energy consumption (with regenerative substations)

Fundamental ideas

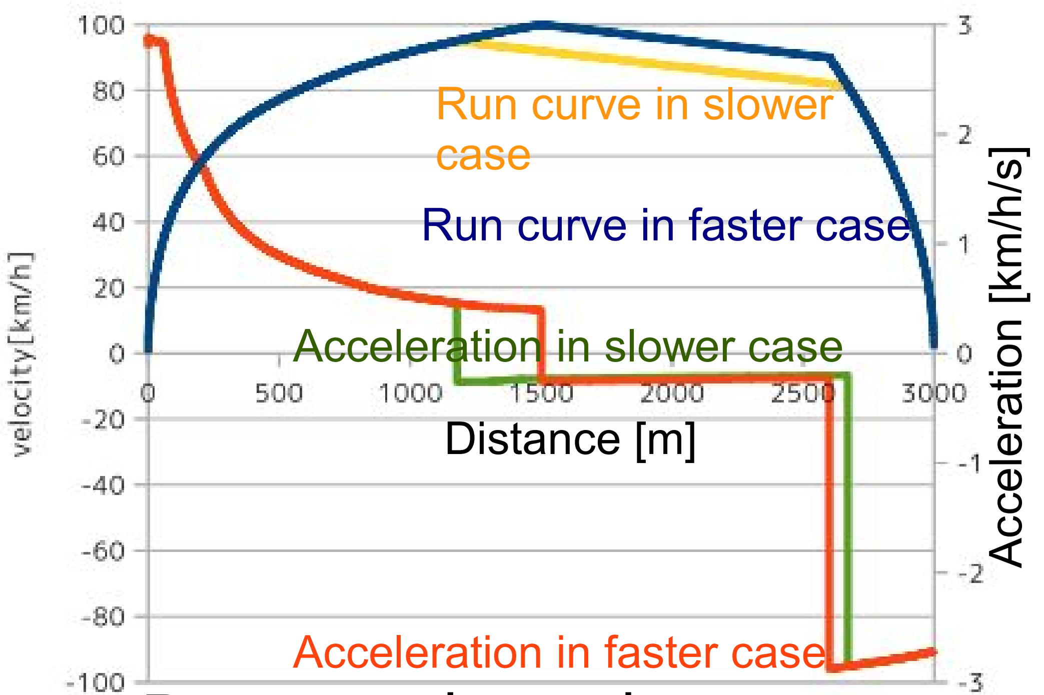
Optimal energy-saving train operation: **Max acceleration, coasting and max deceleration**

Deterministic operation

Where is "buried gold"?---Substantially conservative operational plans!

Notch-off position and brake-starting points

Avoidance of strong brakes at high speed



Power-saving train run-curve

JRTT project: Leader Dr. Mizuma

Power management for sustainable low-cost and energy-saving railways

Theory of power management

KOSEKI, Takaumi
The University of Tokyo

Traction control and onboard energy storage

KONDO, Keiichiro
Chiba University

NTSEL
Project leader: Dr. Mizuma

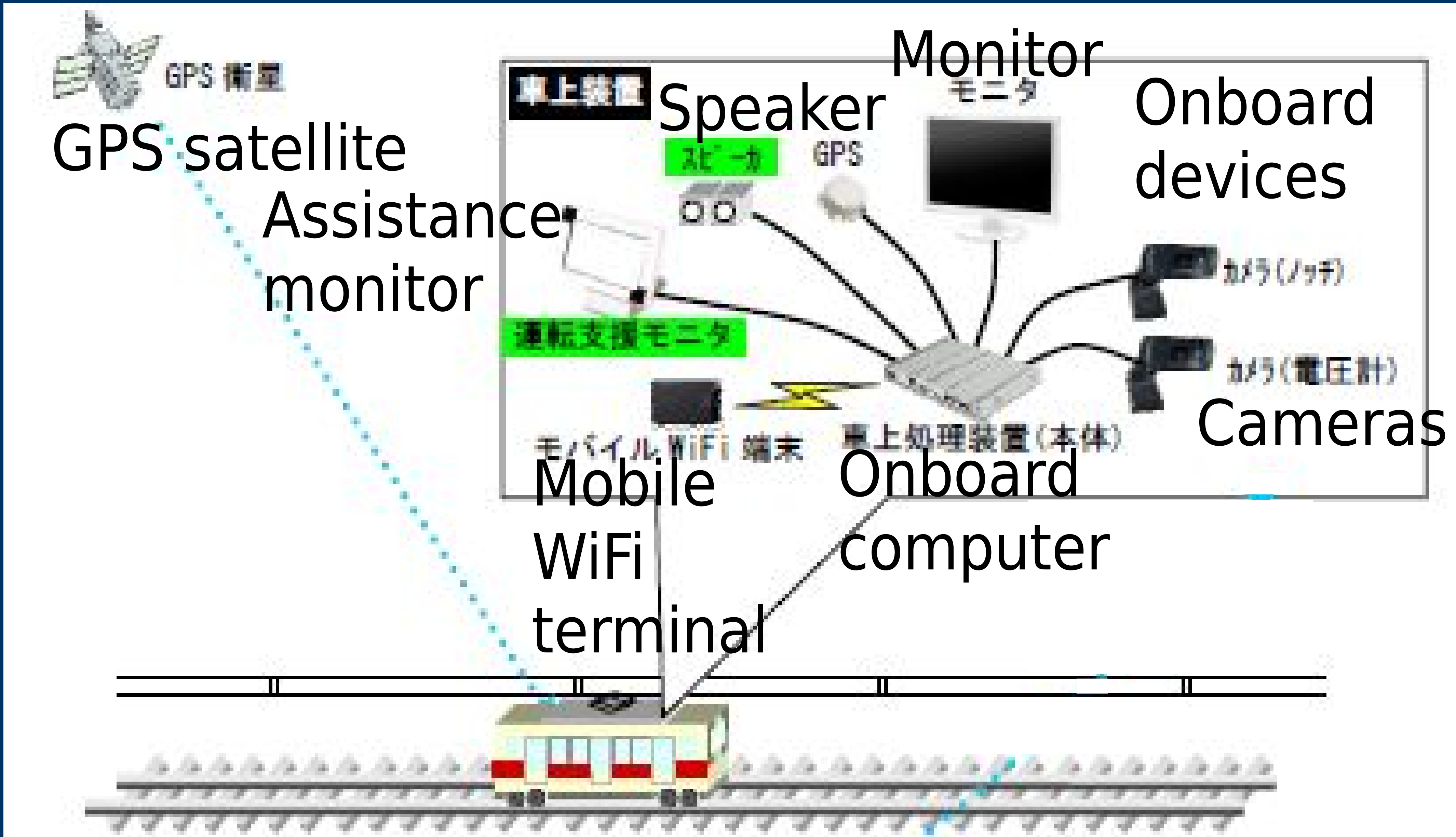
Study on technical needs
Vehicle test

Shinkeisei Raiway Co. Ltd.

Onboard drive assistance

NTSEL

Drive assistance



Advantages of power-limiting brake and its difficult operation

Modification of run-curve and traveling time

Avoidance of strong brake in high speed

Slightly longer traveling time

Enhanced ratio of electric brake usage

Higher provability of avoiding electric braking cancellation in light load conditions

Difficult operation for a driver

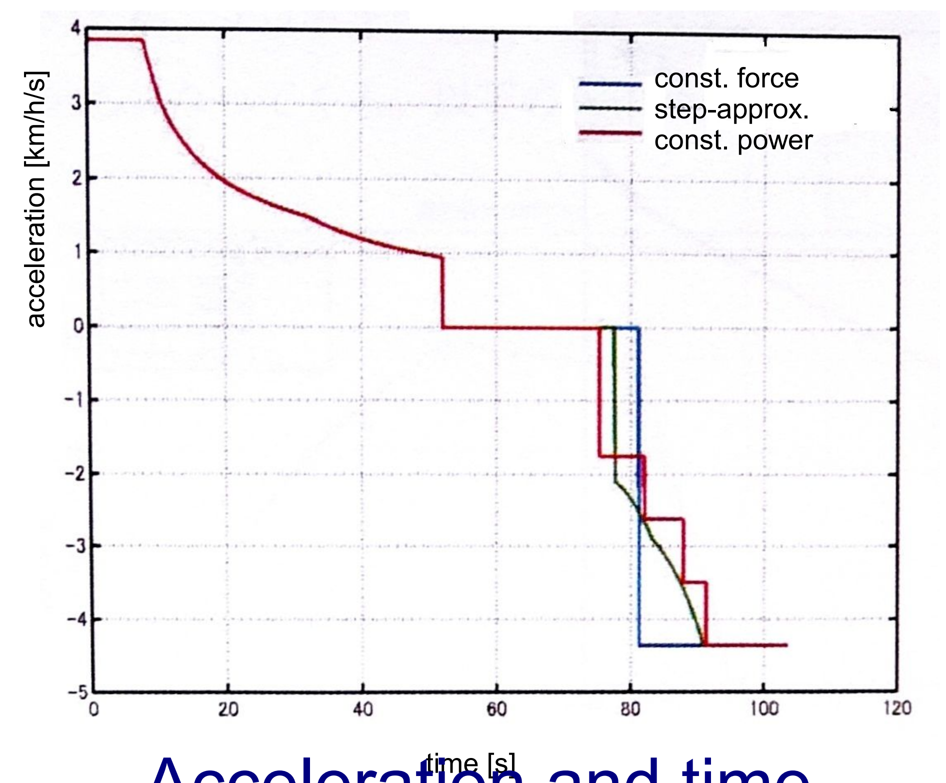
Braking from weak to strong

===> Complicated

Earlier braking start

Needs for **driver advisory system**:

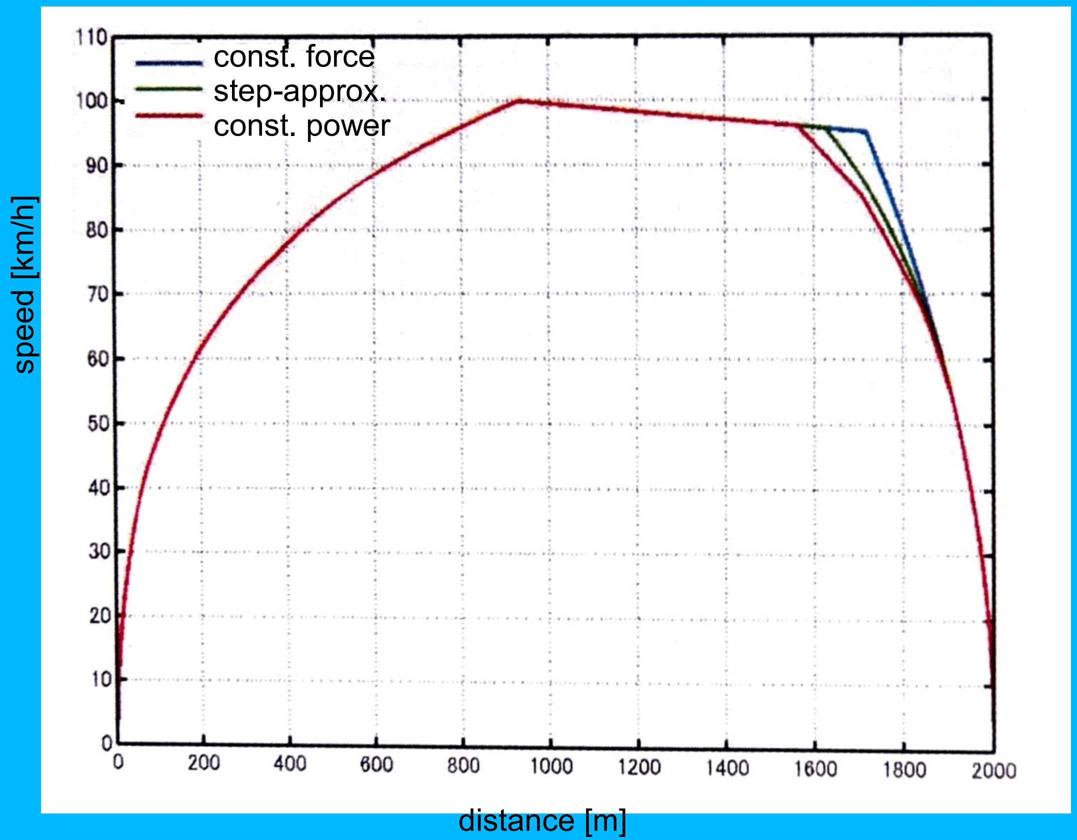
Operation depending on actual initial accelerations



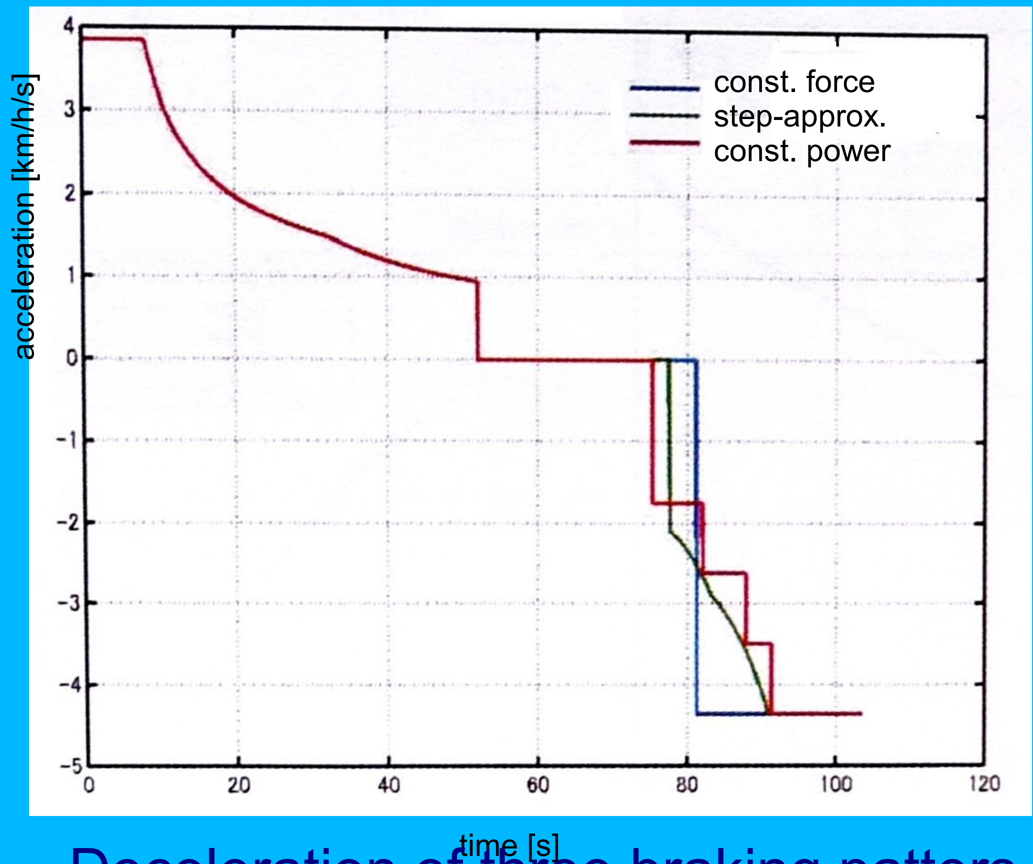
Acceleration and time

Fundamental case study: Scenario

Max deceleration 4.4kn/h/s, max speed 100km/h
Flat inter-station section of 2000m, traveling time approx. a hundred seconds
(1) Full notch braking at high speed
(2) Continuous power-limiting brake
(3) Stepwise power-limiting brake: **Approximate constant power brake at high speed**



Run-curves of three braking patterns



Deceleration of three braking patters

Human interface: display and vocal guidance

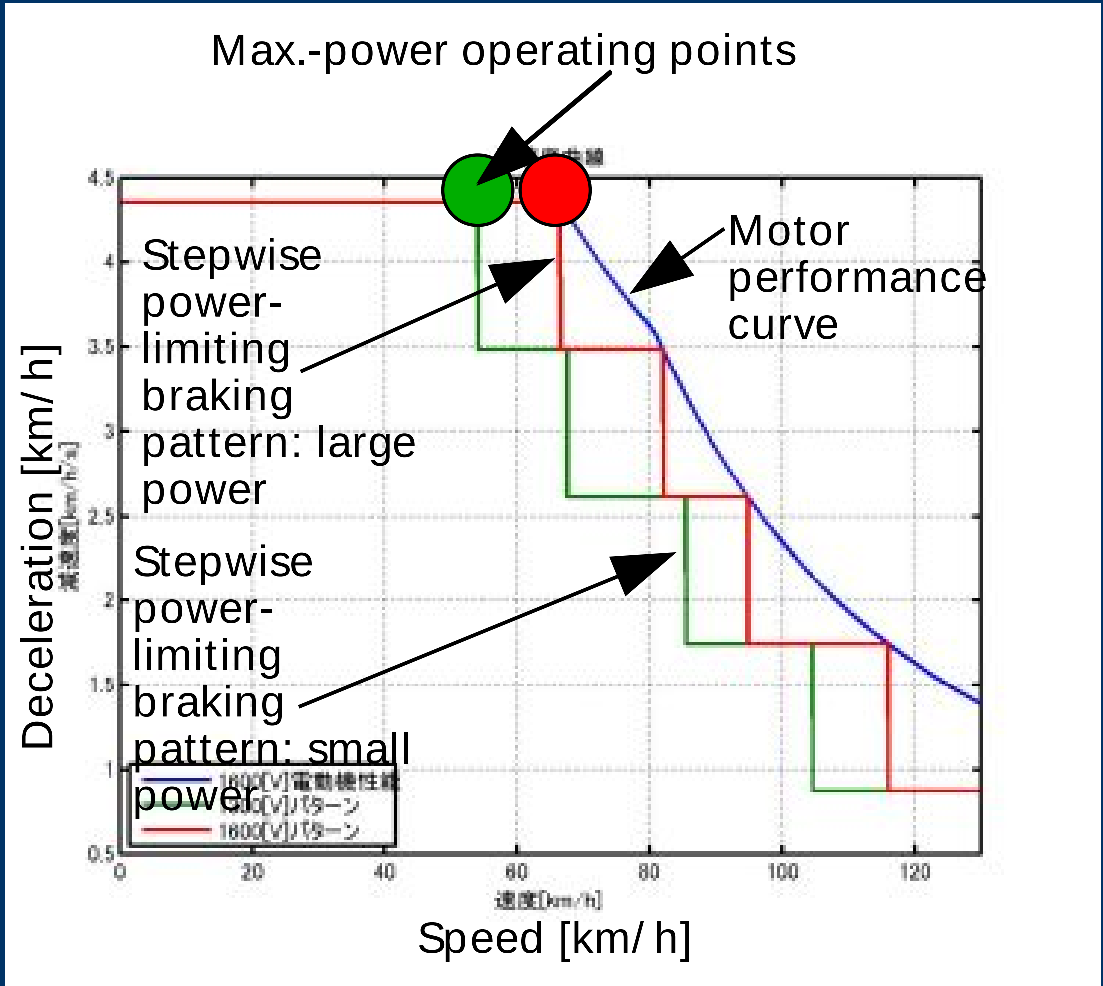
Concept for producing assistance info

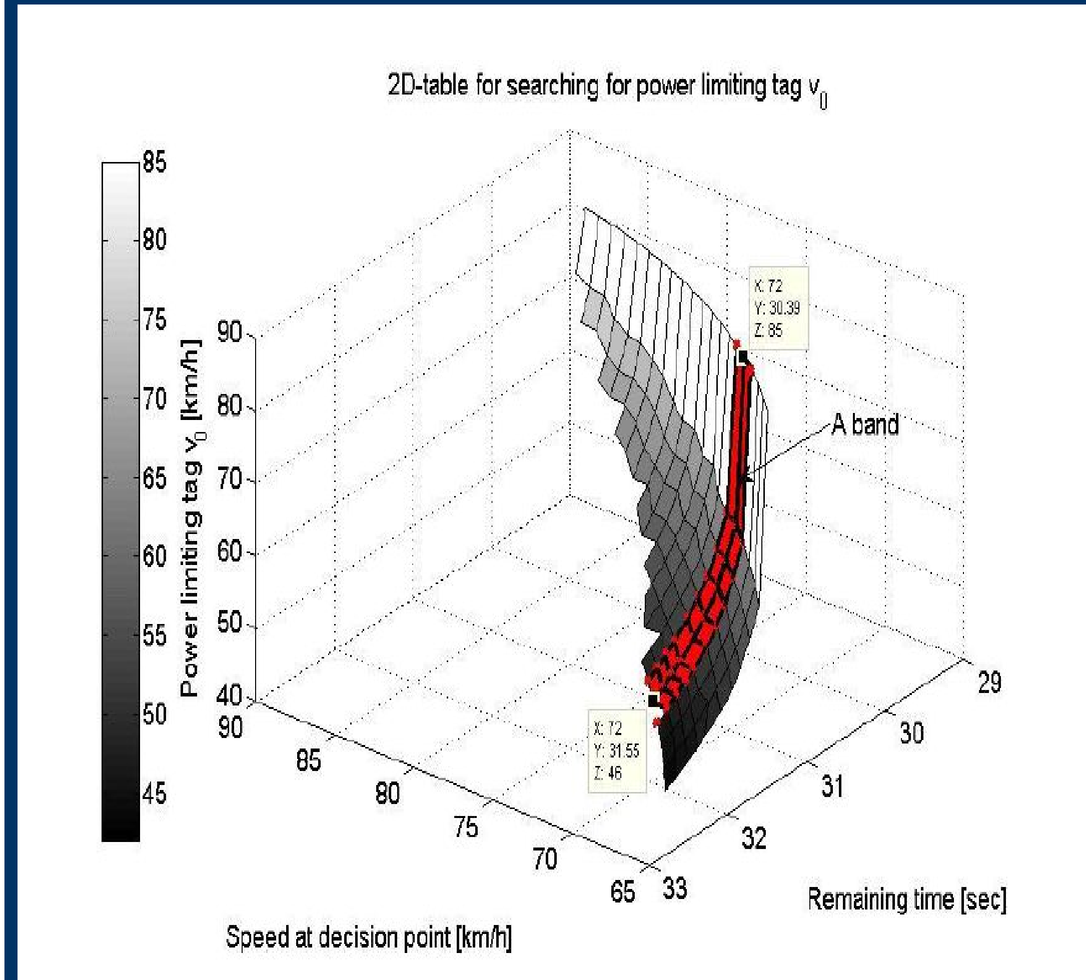
Vehicle test for human-friendly assistance 2012/10/12-15

Double layer database-files

Two dimensional table:

speed, time-reserve to braking-power limit index

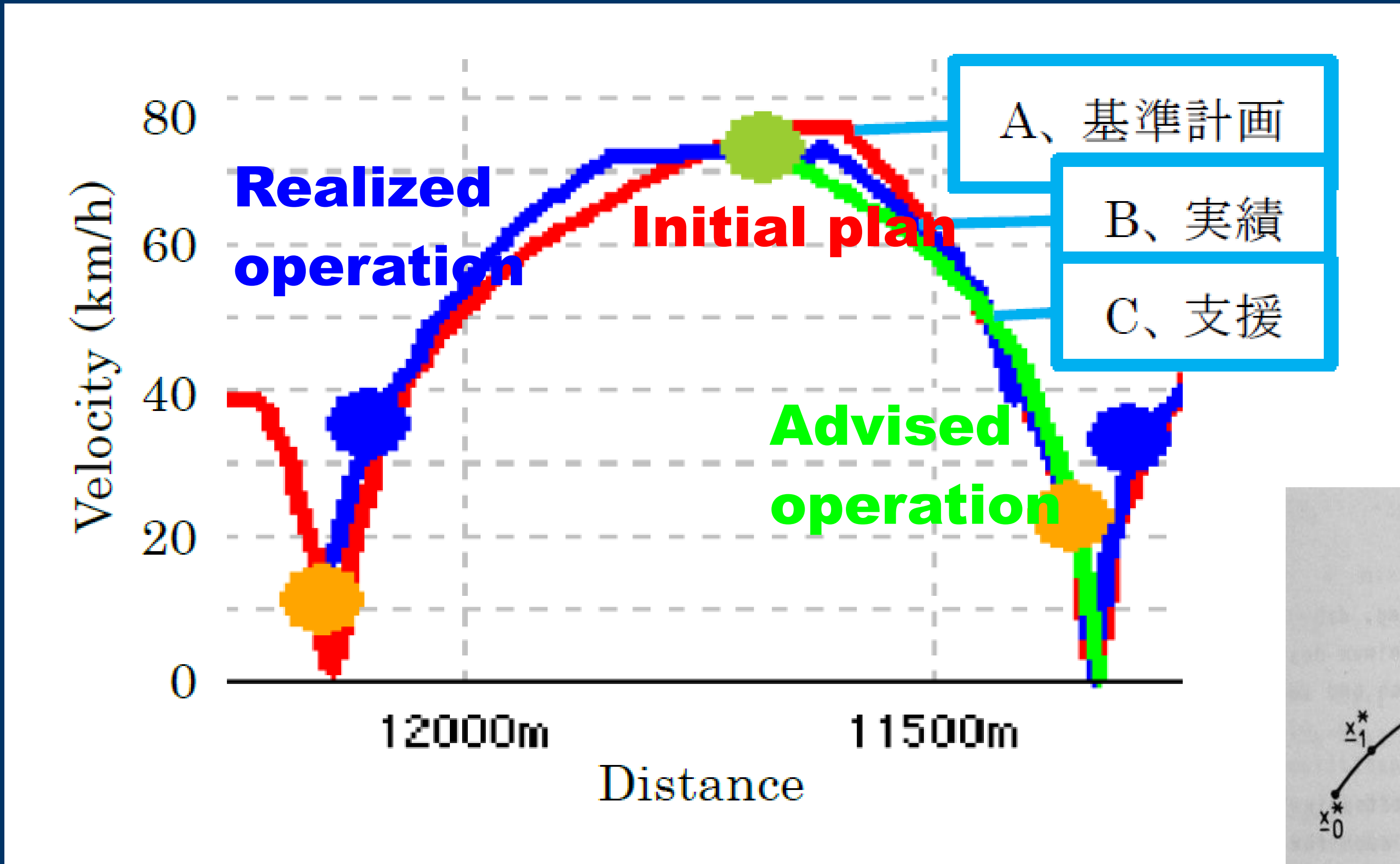


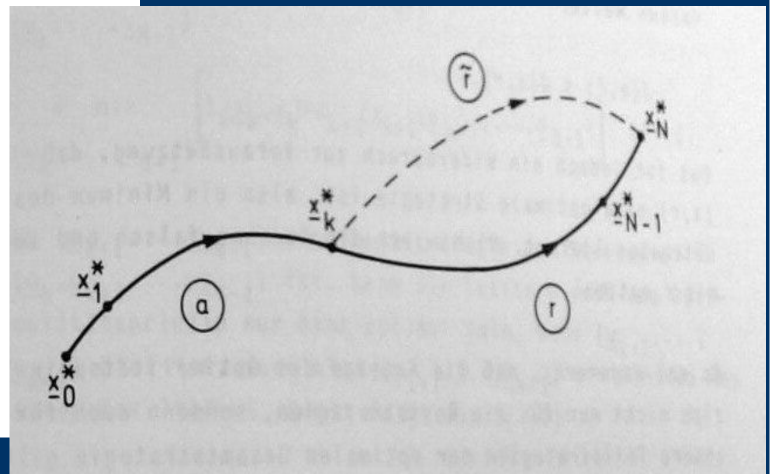


Assist starting point

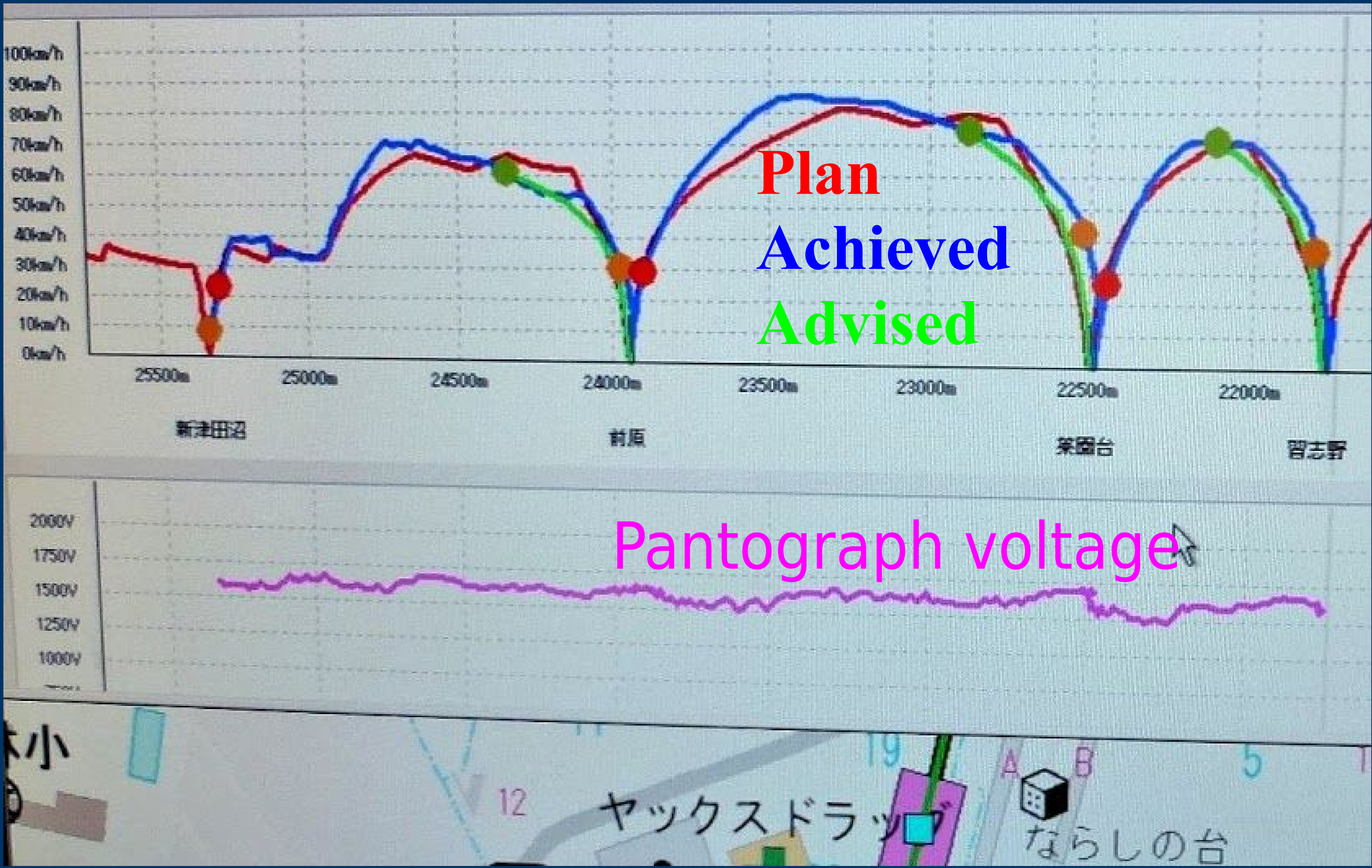
Fixed assist starting point
Passing speed and time reserve
=>Braking notch index

Identical idea to DP by R. Bellman
Necessary condition for optimality

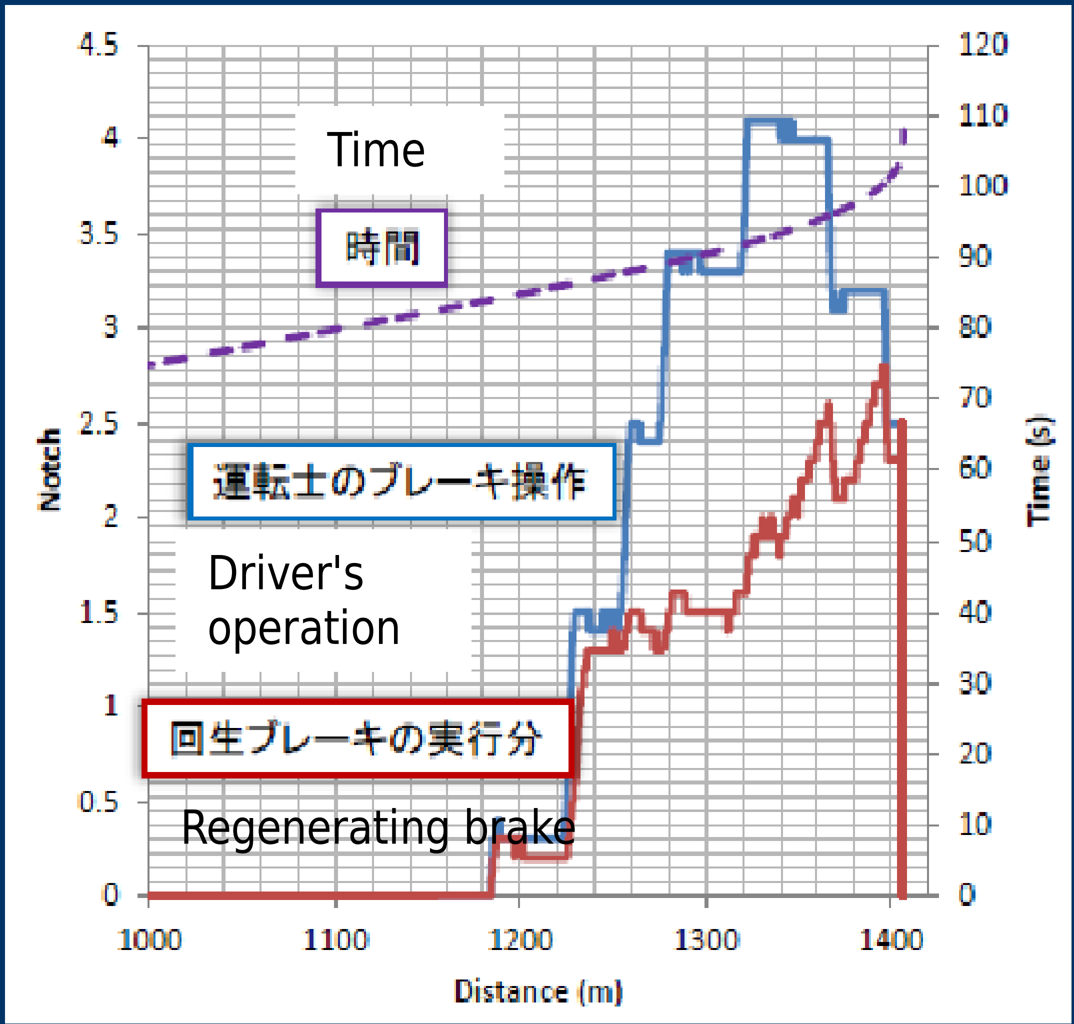




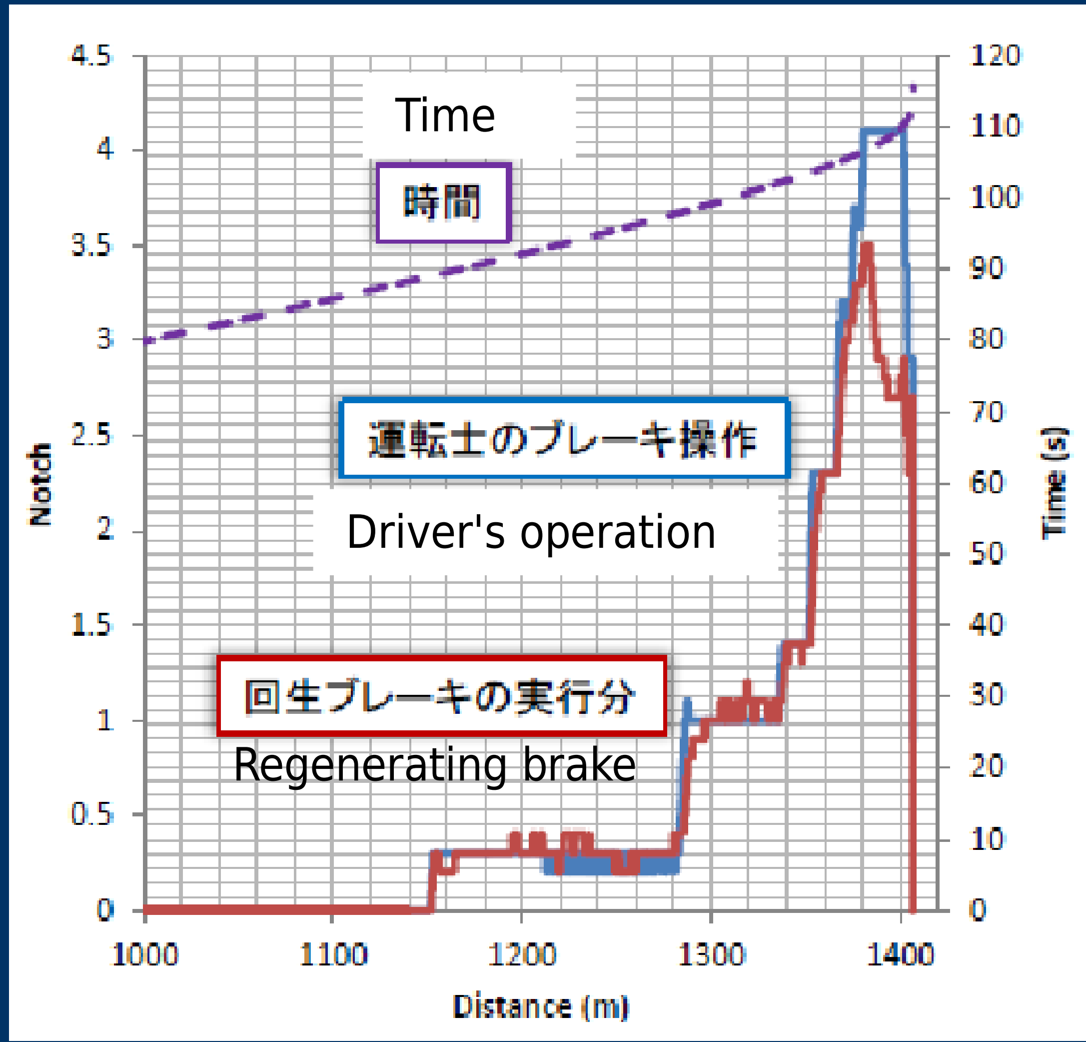
The third vehicle test in October 2012



Test results
Action of regenerative brake

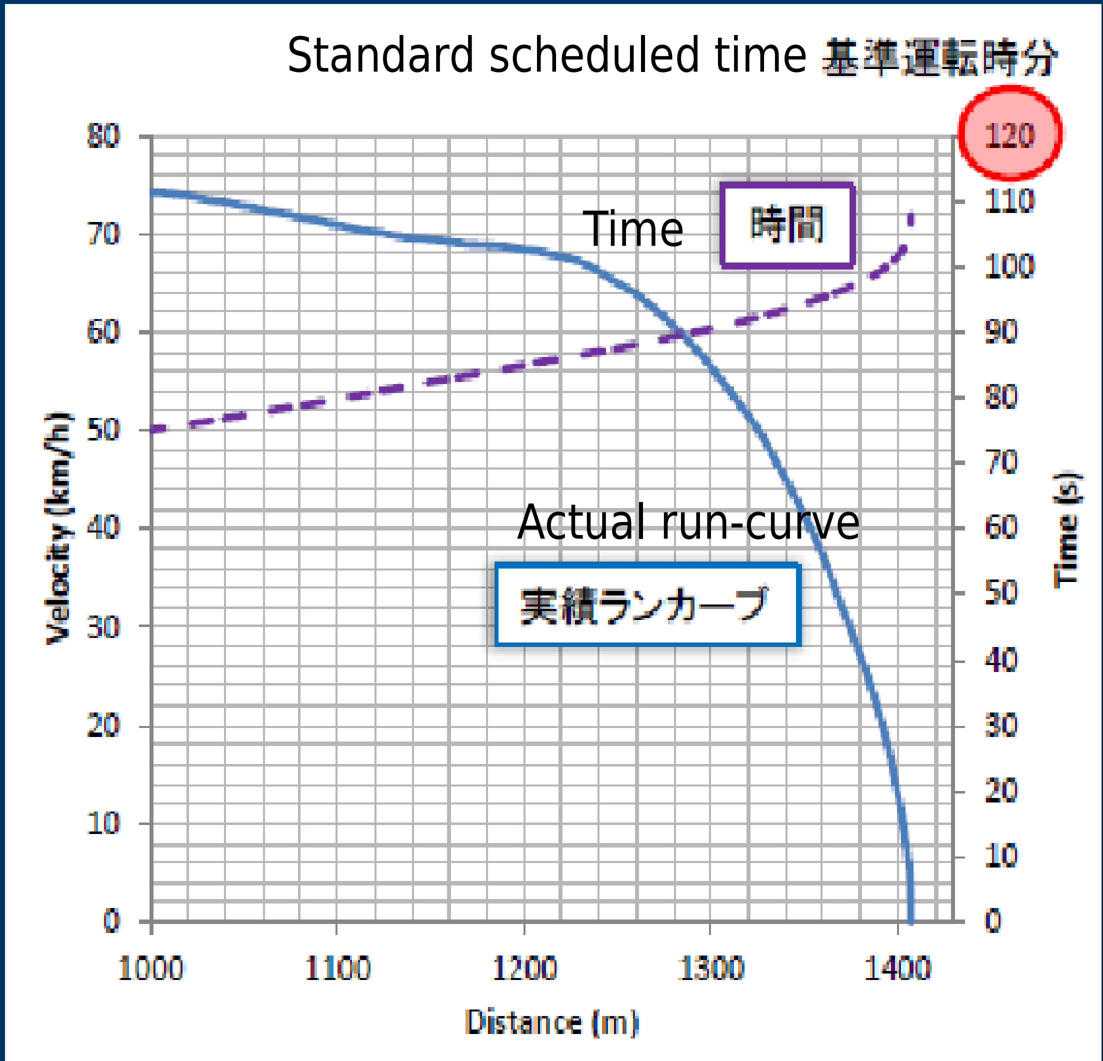


Braking without assistance

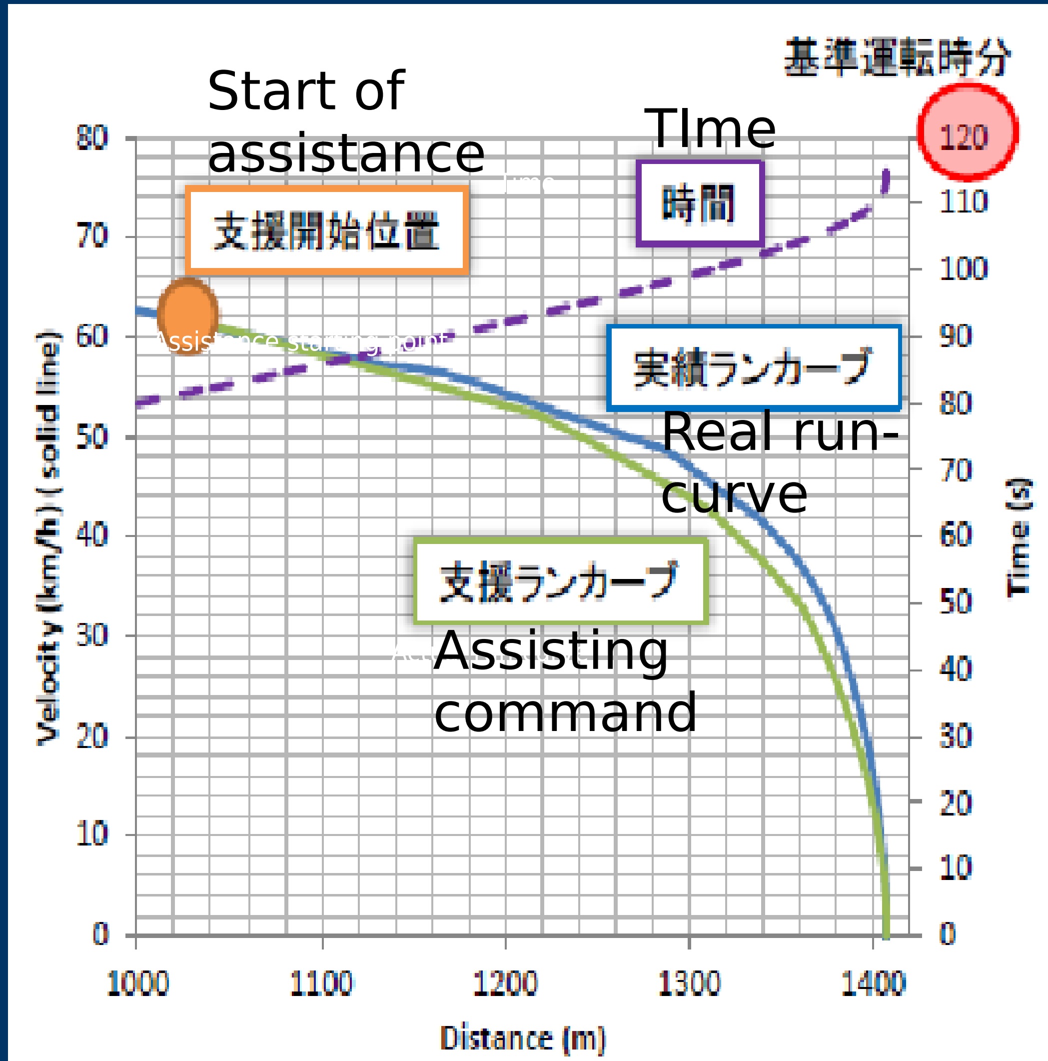


Braking with assistance

Comparison of train run-curves



Braking without assistance

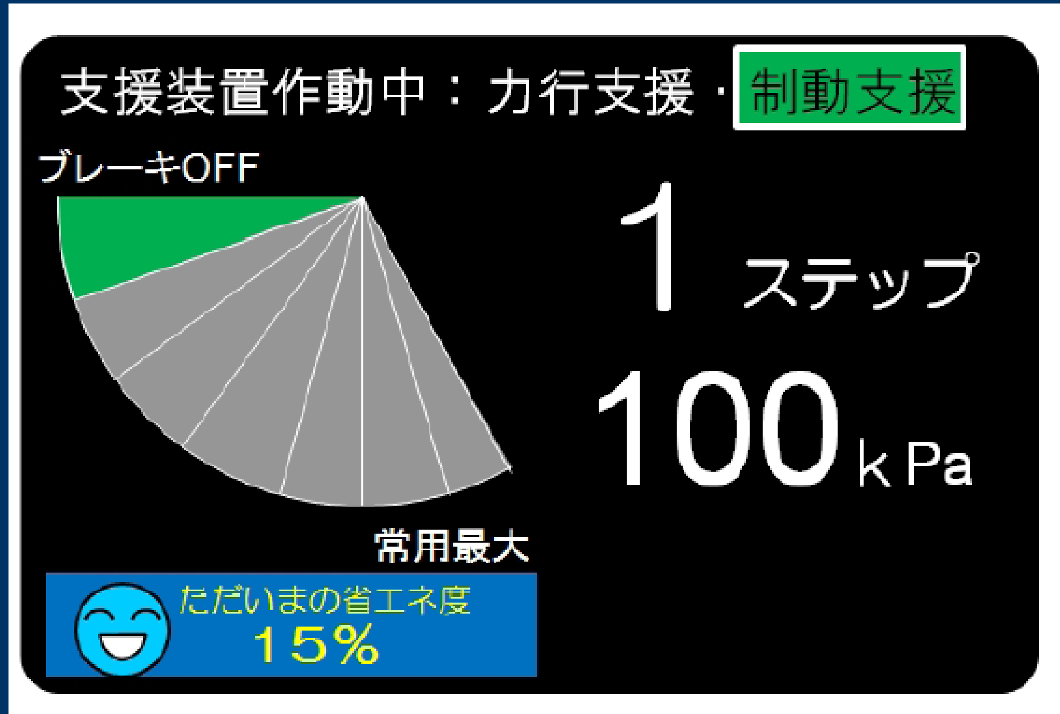


Braking with assistance

Opinion from train driver: problems

○Assist display
- Good to understand
- Info on regenerative loads is useful
- Info on energy-waving achievement gives motivation

○Assist timing
- Loss time by vocal guidance
- **Earlier advises are** requested: *2 sec.*
-



○Advisory contents
- Assist start in arriving station is awful.
- Intermediate feedback of the achievement: *incentive of drivers*

Power management and energy-saving Automatic Train Operation for linear metros

2014-2017

Introduction

1) The technical development of Japanese linear metros started in **1979**.
2) After the commercial operation in the 7th line **at Osaka in March 1990**, the technology has been extensively applied: commercial line of 115km in Japan.
3) Japan has the longest commercial line of linear subways.
4) LIM has much worse efficiency and power factor.
5) Larger traction energy demand is a major problem.
6) Japan Subway Association (**JSA**) started technical investigation to realize more efficient linear metro systems in 2010.
7)Let us **improve running profile by its automatic train operation (ATO)**.

Background

Iron Wheel/Rail System with Linear Induction Drives

Global market :Bombardier system

Starting from Skytrain in Vancouver, the business market is now extended to Malaysia, Singapore, China, Korea,...

Bombardier has its own test line for operational test and training at Kingsto, Canada.

Korean application

Revenue service 2009(?)
11.5lm dual-lane alignment
15 stations
30 ART MK II vehicles

Global market: Southern-eastern Asia

PUTRA line in Malaysia

シンガポール、マレーシアには Bombardier社システム導入実績が既にある

Bombardier has already supplied commercially operated systems in Singapore and Malaysia.

Global market: CHINA

中国は .....

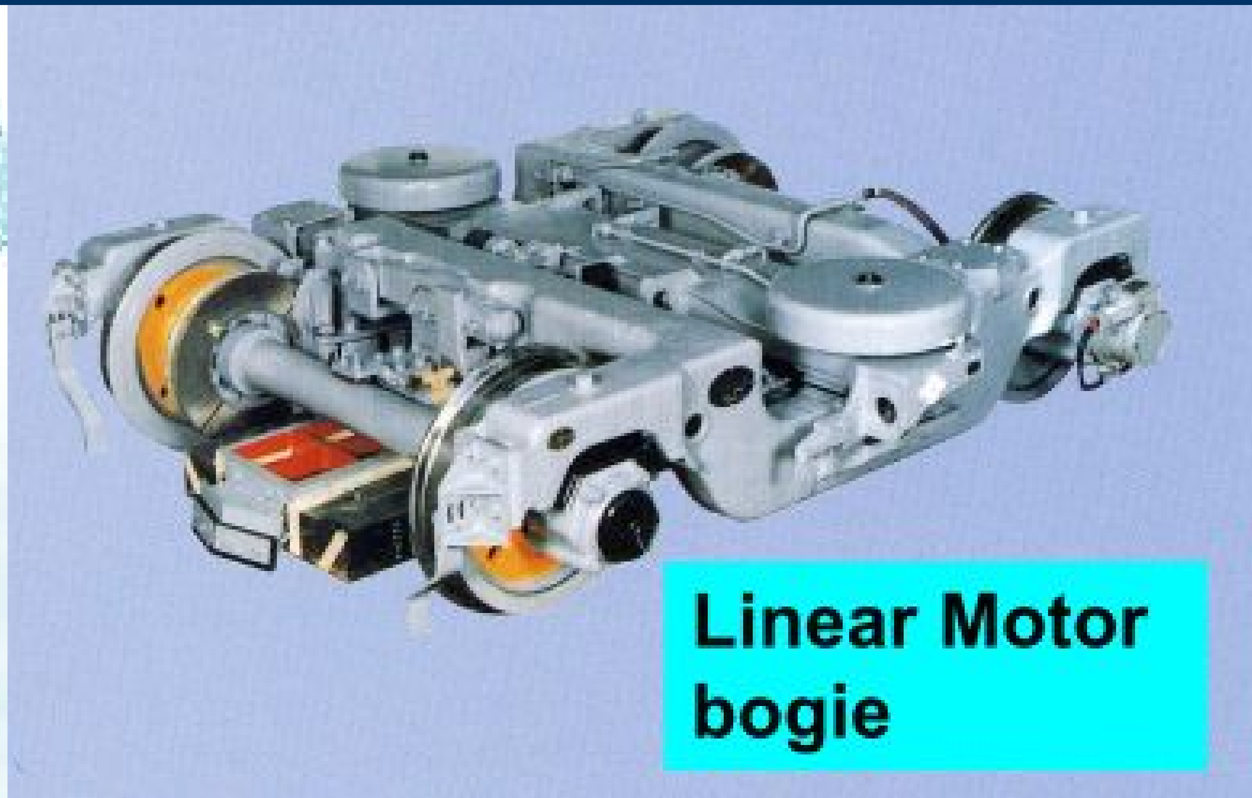
Chinese linear metros

Source: Bombardier

Japanese Linear Metros

the Largest Linear Driven Train Network

Linear Metros
being developed from 1979



Source: Japan Subway Association

The Fisrt application: Osaka-Nagahori-Tsurumi-Ryokuchi Line

March,1990
5.2km partially opened

August,1997
15.0km whole line opened

17 stations

4cars × 25units

Source: Japan Subway Association

Depot for Osaka Imazatosuji-Line. (Technical visit by IEC/PT62520 members)

December,2006

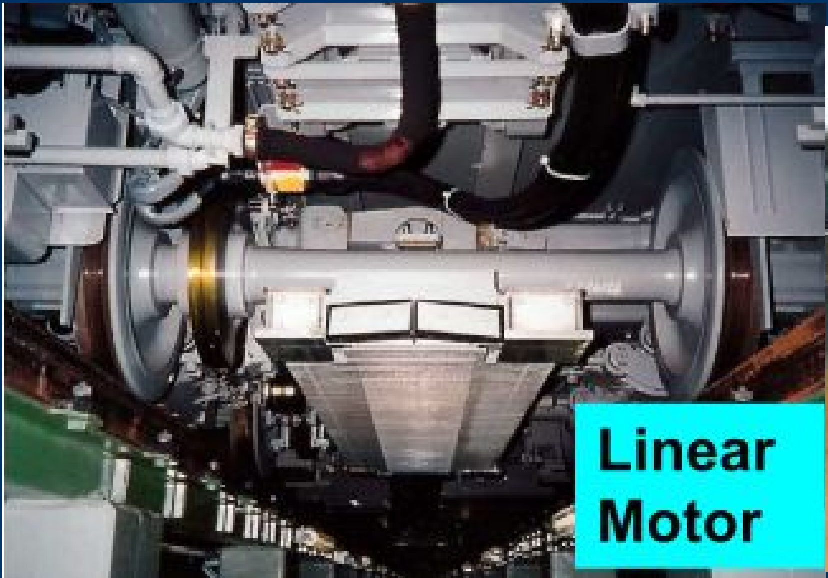
11.9km partially opened

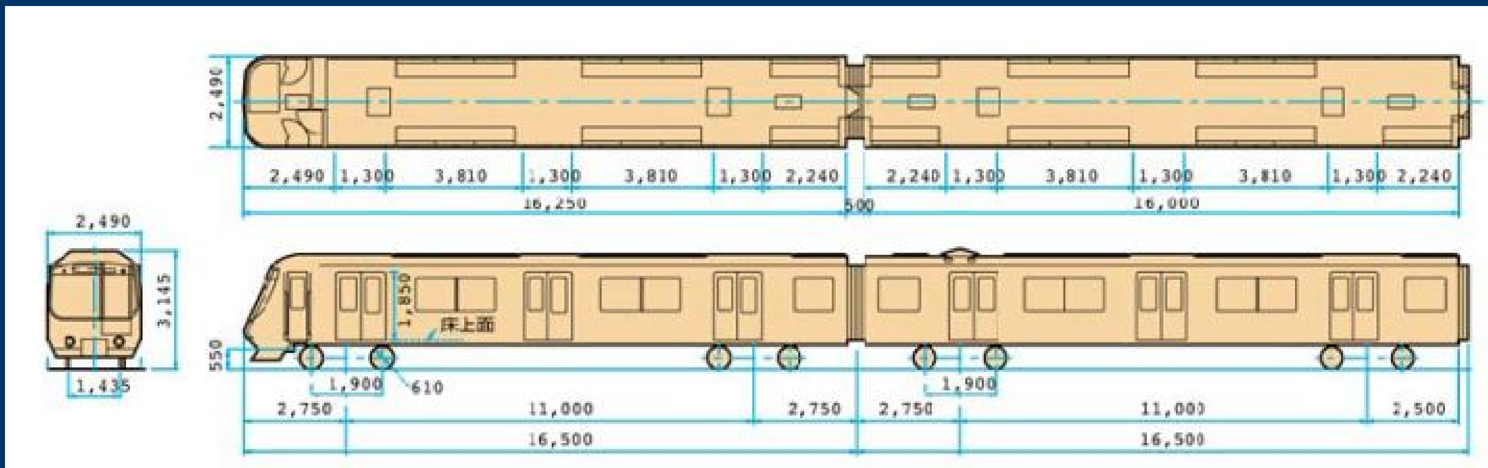
11 stations

4cars × 20units

Source: Japan Subway Association

Tokyo Ring Transport
Oedo-Line: Japanese standard vehicle





December,1991
3.8km partially opened

December,2000
40.7km whole line opened

38 stations

8cars × 53units

Japanese standard rolling-stock Source: Japan Subway Association

Kobe-Kaigan-Line

Source: Japan Subway Association

July,2001
7.9km opened

10 stations

4cars × 10units

Fukuoka Tozai-Line (The 1st DTO-ready system)

February,2005
12.0km opened

16 stations

4cars × 17units

Driverless System

Source: Japan Subway Association

Yokohama Green Line

March 2008

13.1km

10 stations

4cars × 17units

Source: Japan Subway Association

Sendai Tozai Line

Source: Japan Subway Association

December 2015

13.9km
13 Stations
4cars X15 unis

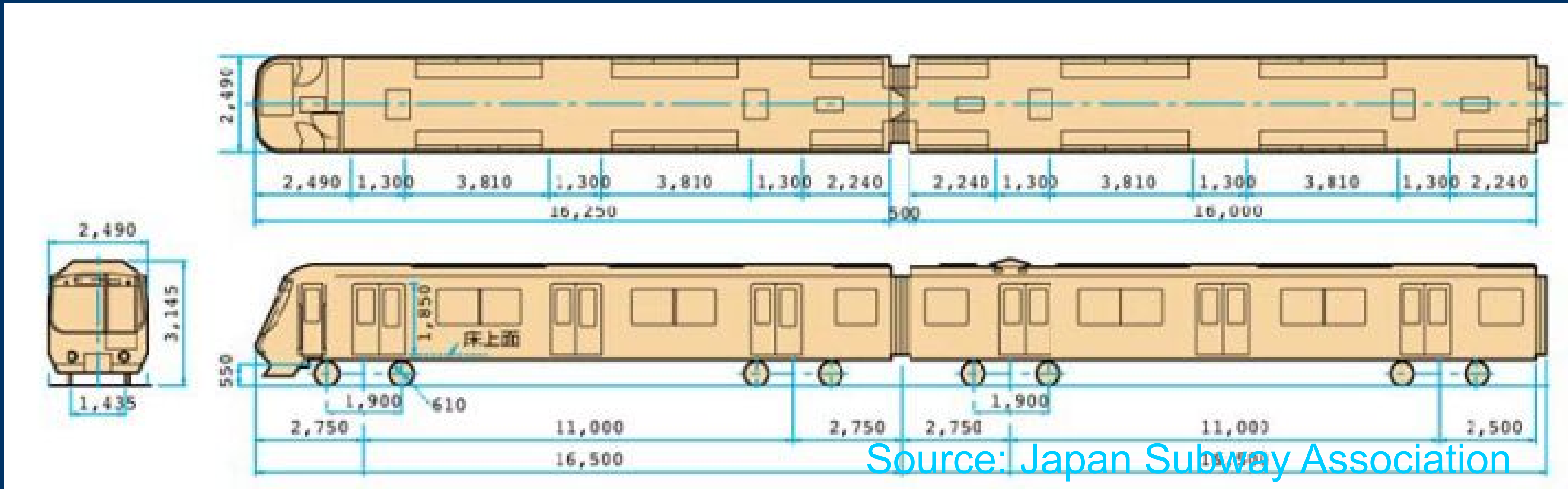
Linear Metros
Total 115km

Technical efforts at Japanese Subway Association

Standard LIM for Japanese linear metros (1996)

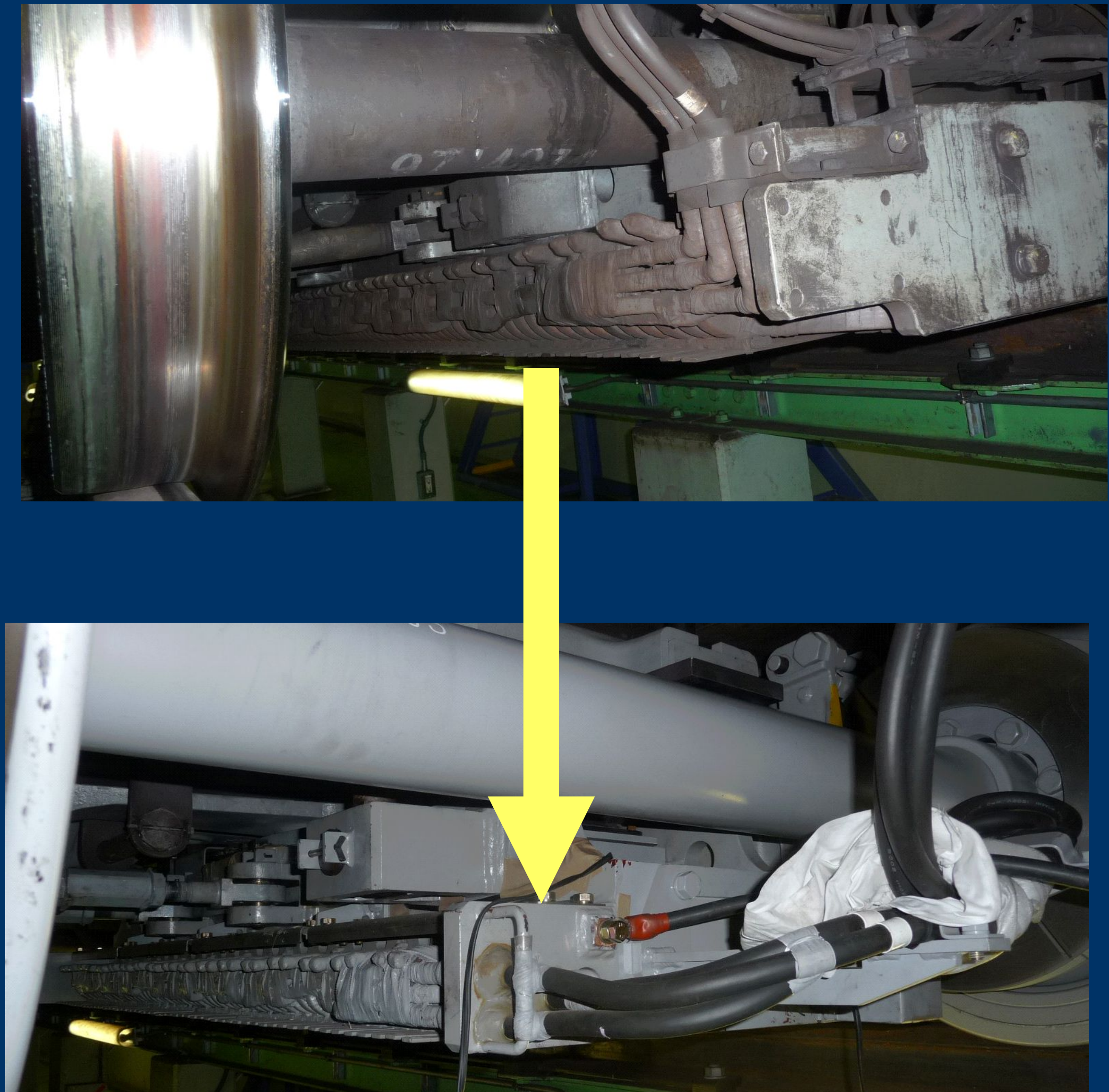
Shorter gap for higher performance (1996)

Eco-rail project (2012-2015)



Japanese standard rolling-stock

Smaller and lighter primary



Changing design priority:

Efficiency to volume

Japanese Linear Metros born in **Osaka**

The 10th “One Step on Electro-Technology” of IEE-Japan

Power management and energy-saving Automatic Train Operation for linear metros

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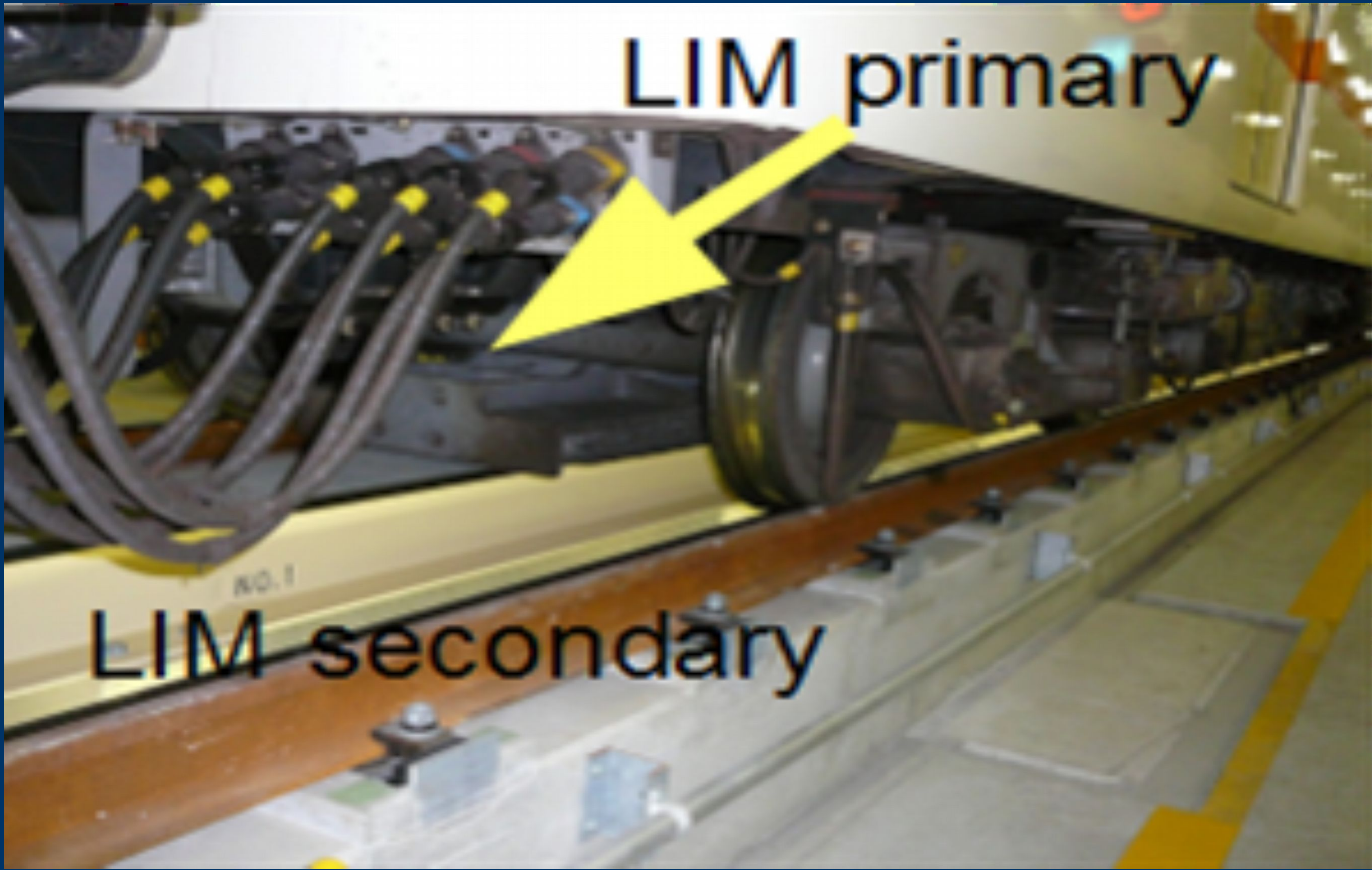
Linear Induction Motor at a linear-metro rolling stock



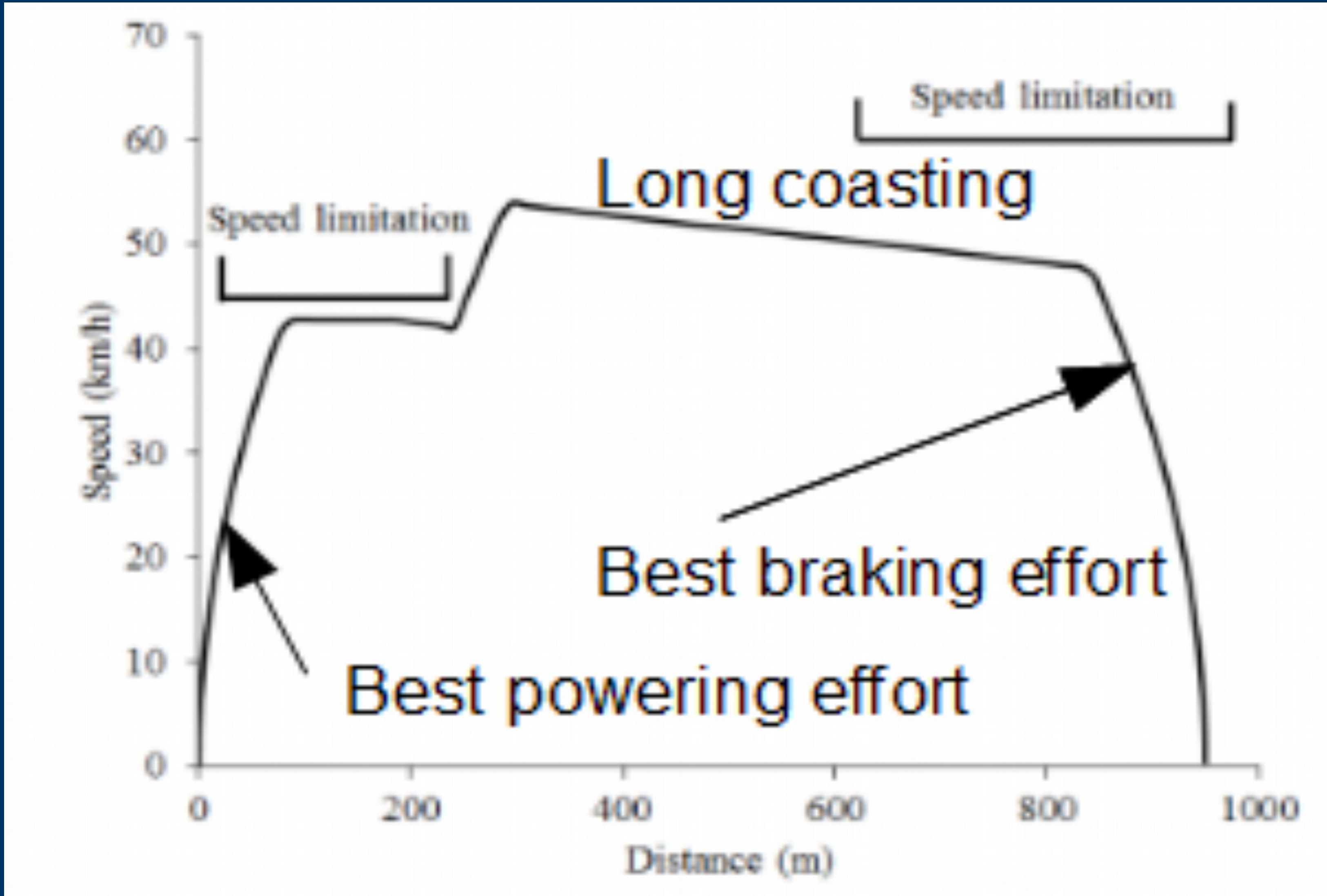
Theoretical aspect

for energy-saving effort

General strategies to reduce energy

1) Improved design of **LIM-primary to reduce weight** of onboard traction component.
2) **Reduction of magnetic gap length** of the LIM.
3) Improvement of the **form and structure of secondary conductor** for reducing secondary resistance, and consequently, secondary loss.
4) Introduction of **novel self-steering bogies to reduce running-resistance** during passing curvatures.
5) Train operation for better power-management!

Fundamental strategies for energy-saving operation

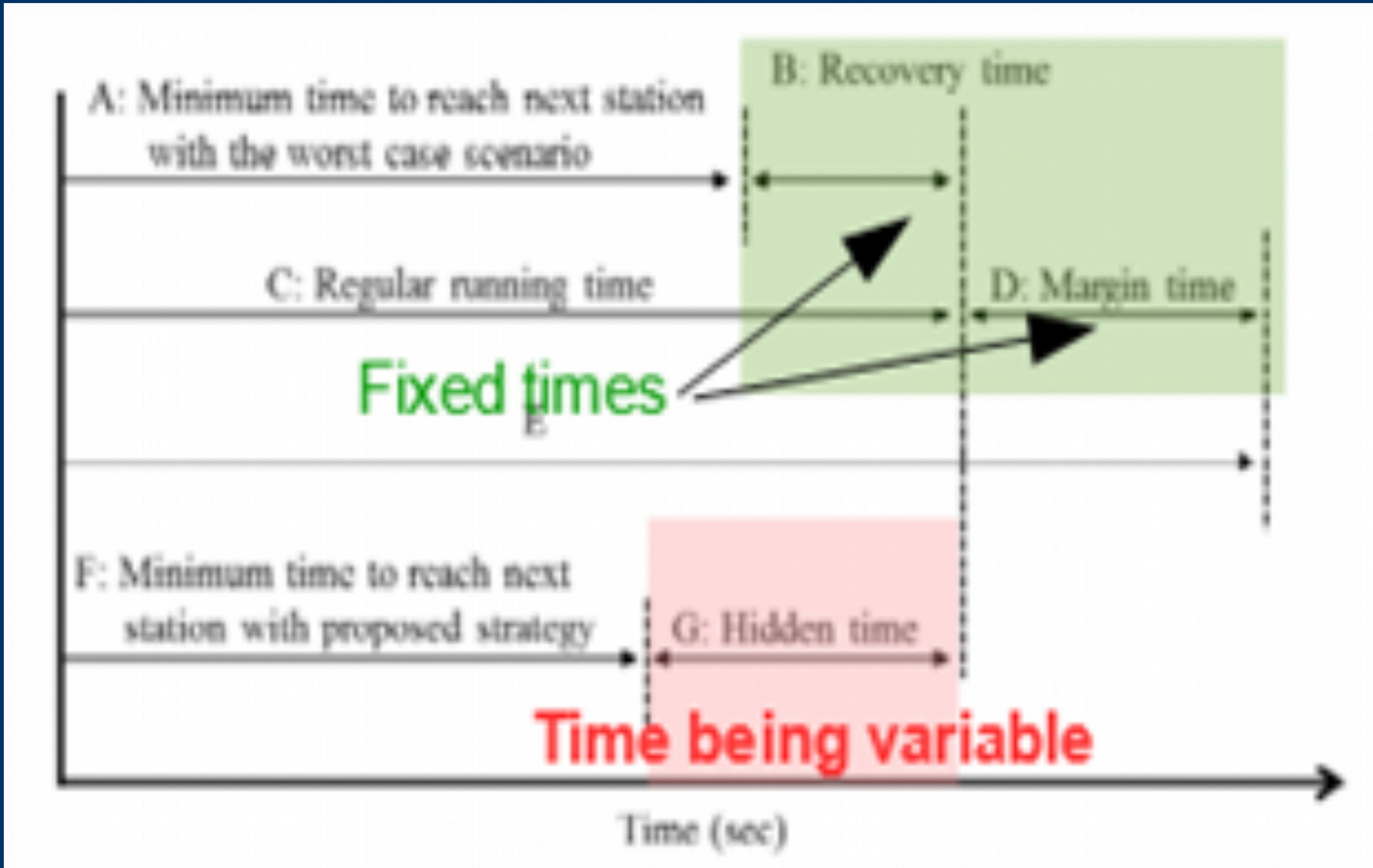


Three strategies for energy-saving train operation

1) introduction of possibly **long coasting** instead of speed- constant weak powering operation at high speed,
2) best use of regenerative brakes, *i.e.*, **power-limiting brake**s at high speed, and
3) selection of efficient powering/braking command inputs, *i.e.*, **combination of the best efforts both in powering and braking** modes in principle. *However,*

Keep the traveling time!

Hidden time for energy-saving efforts



How to dig out "hidden time" for energy-saving

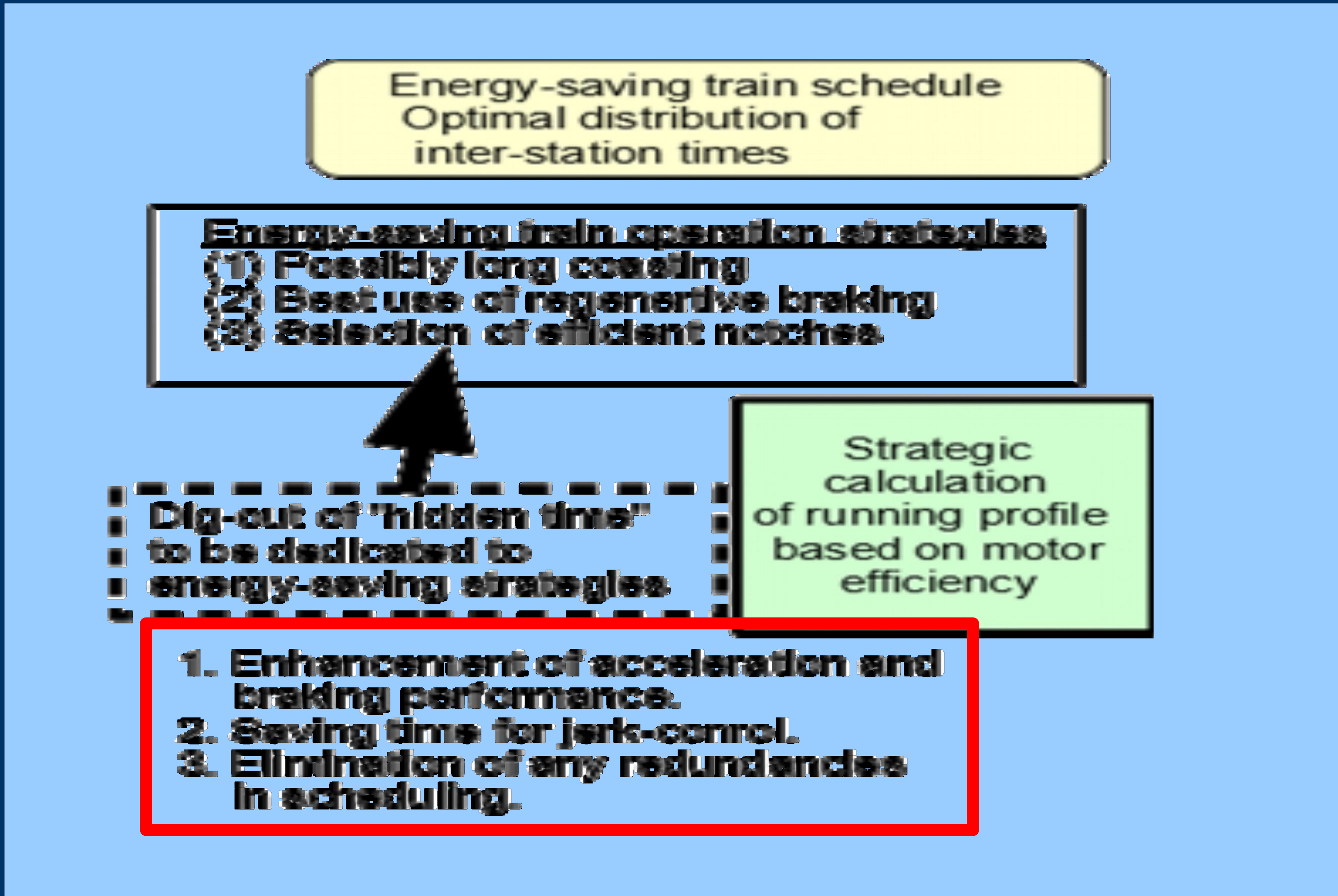


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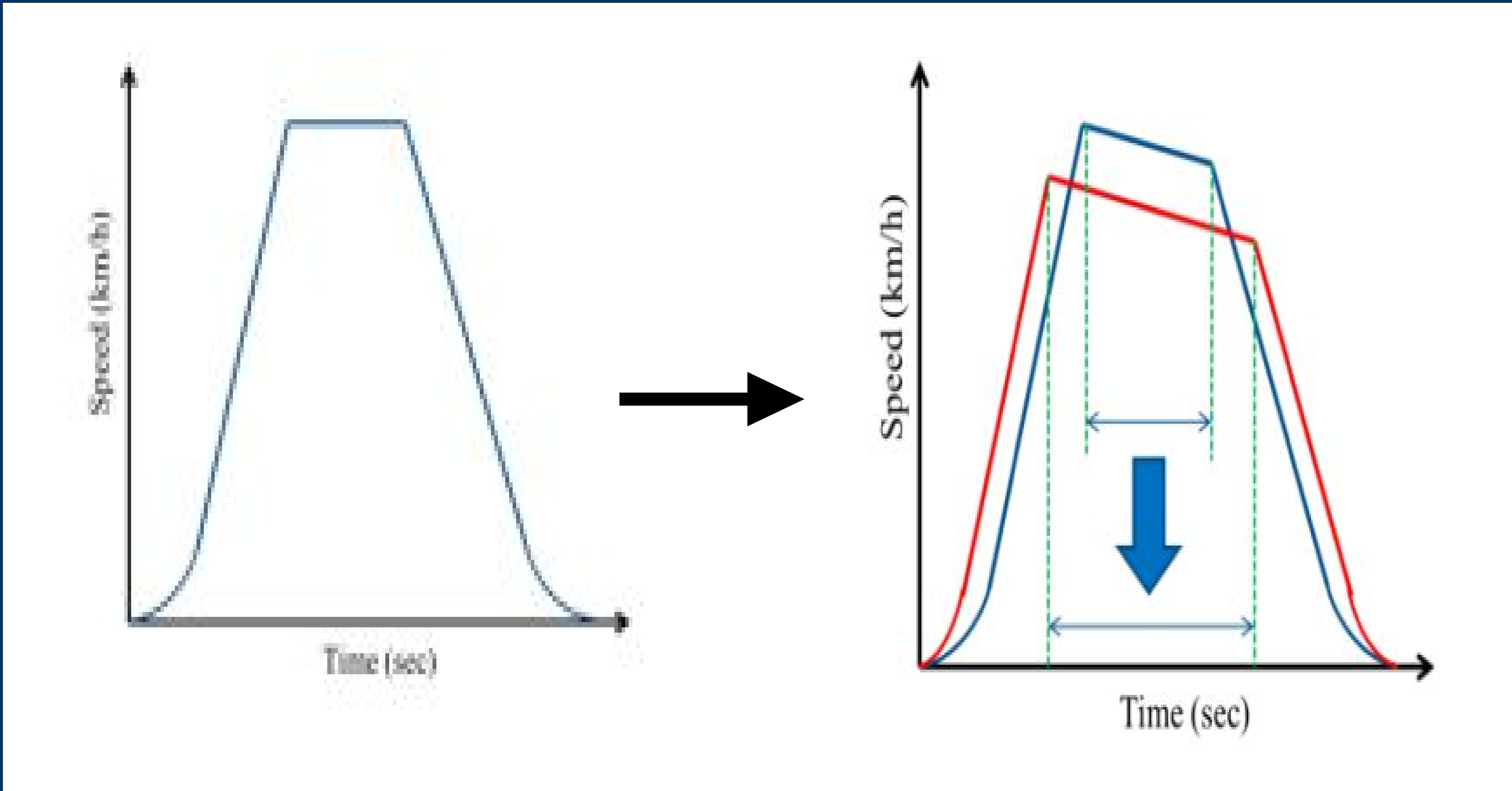
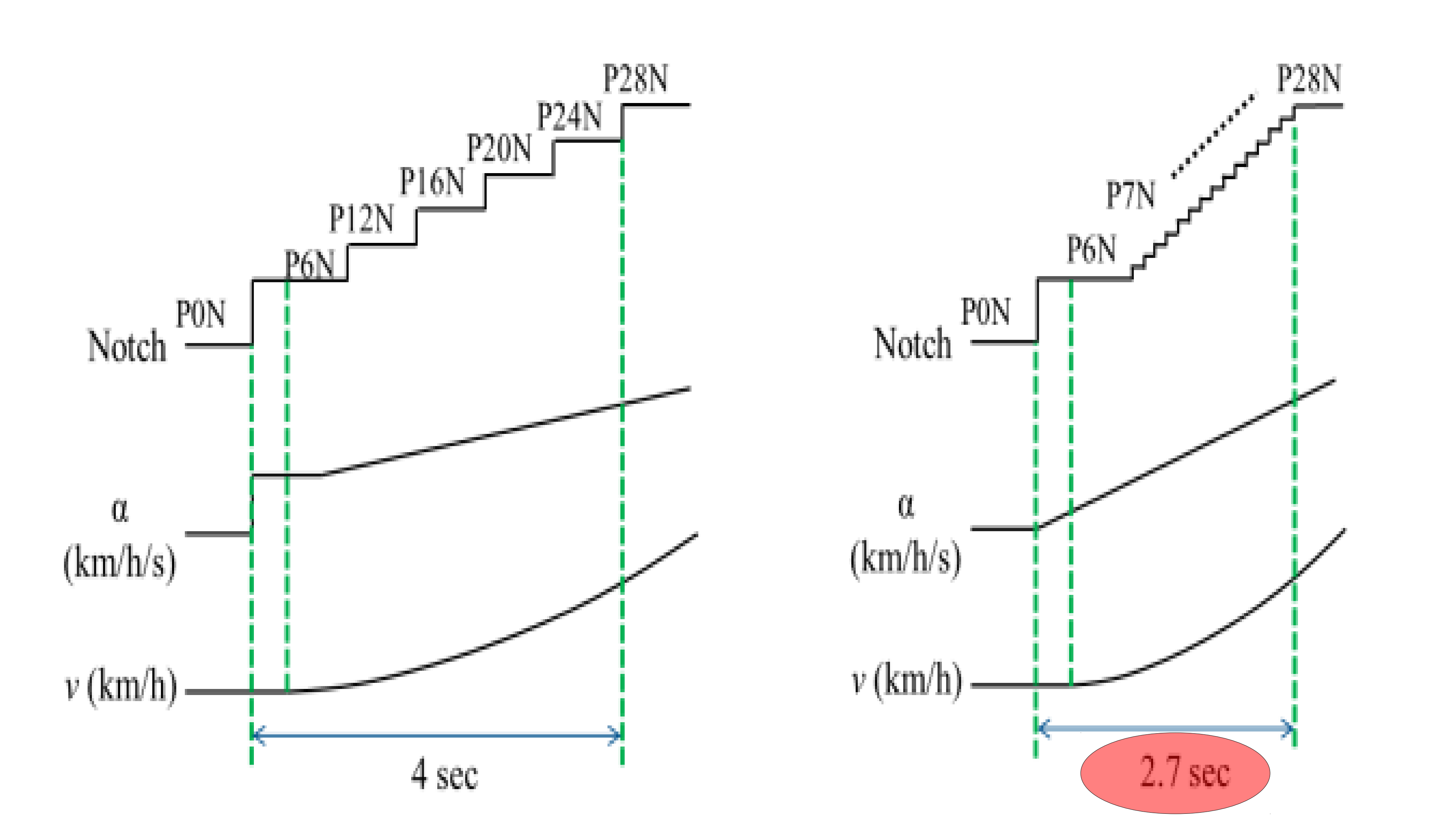
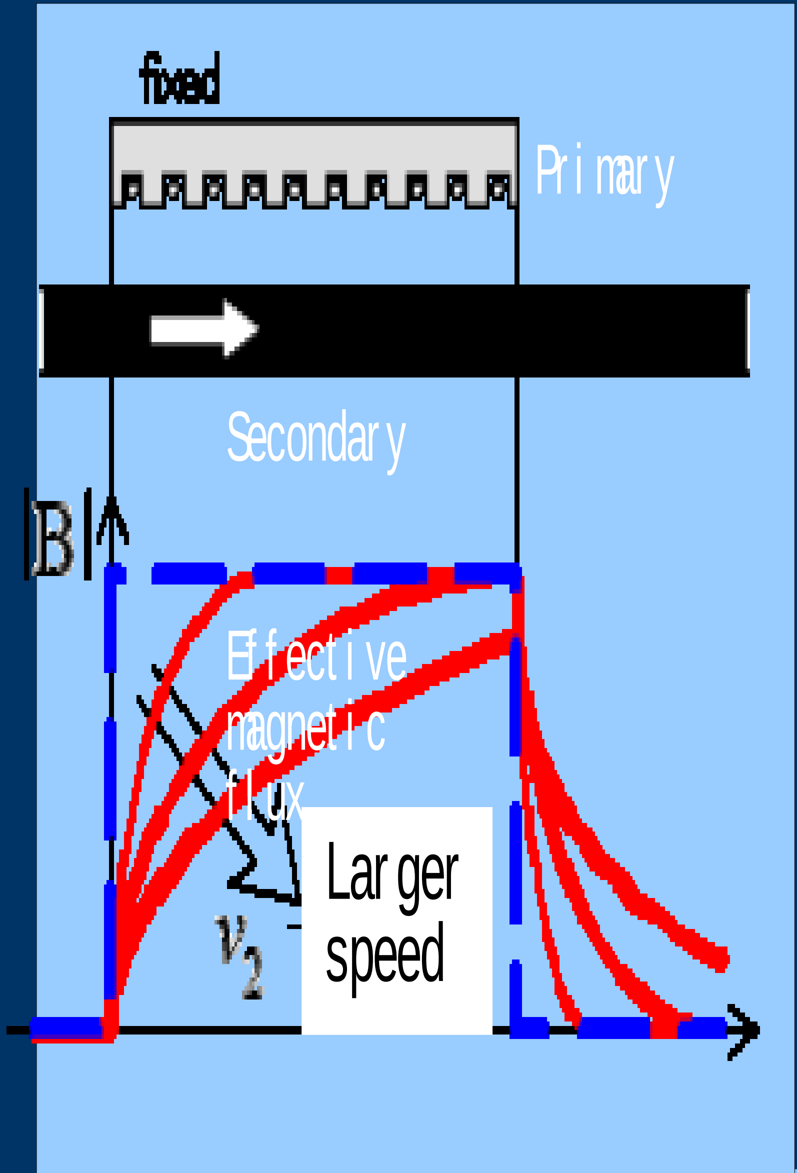
Image of improved running profile

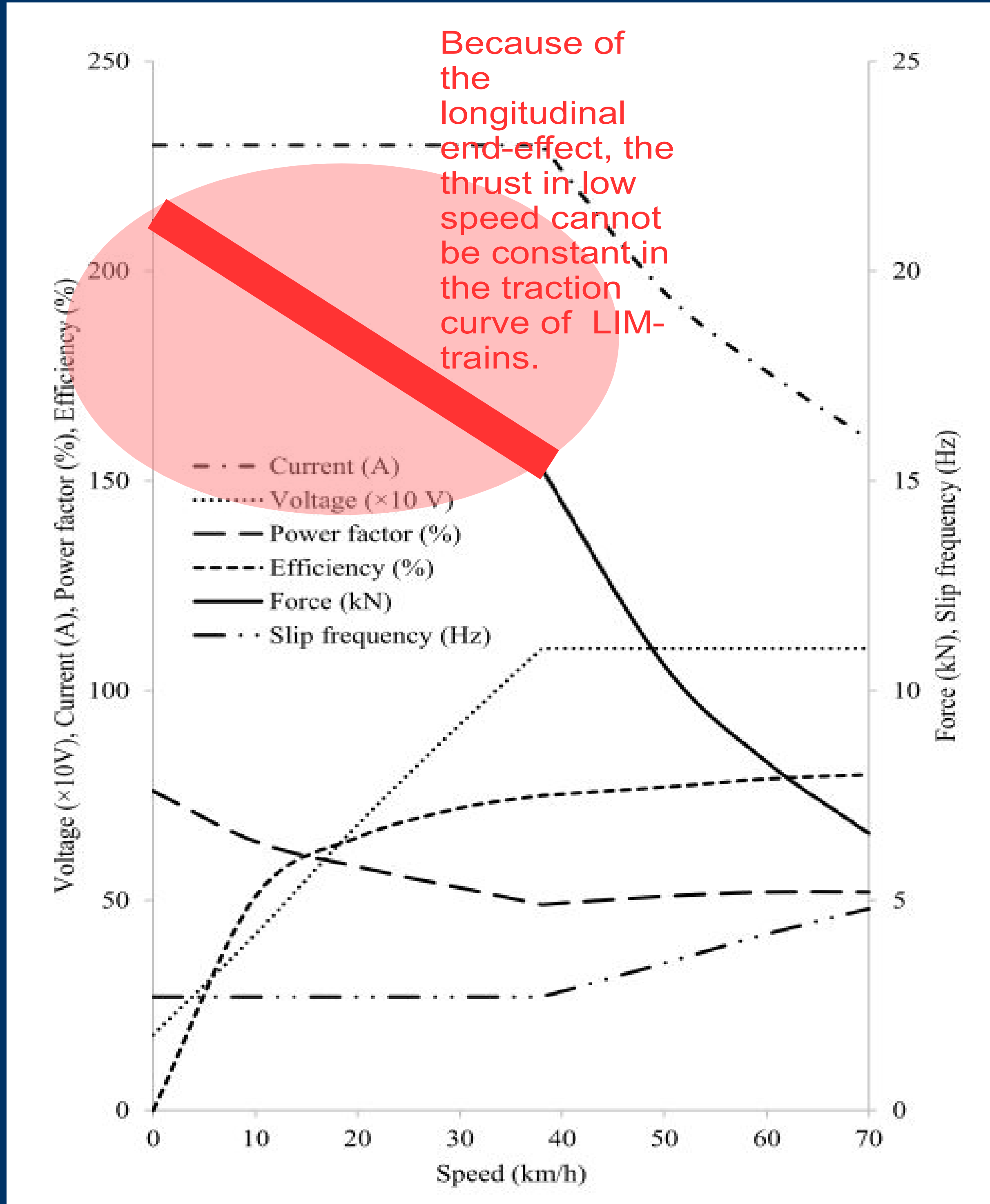


Fine and shorter jerk control

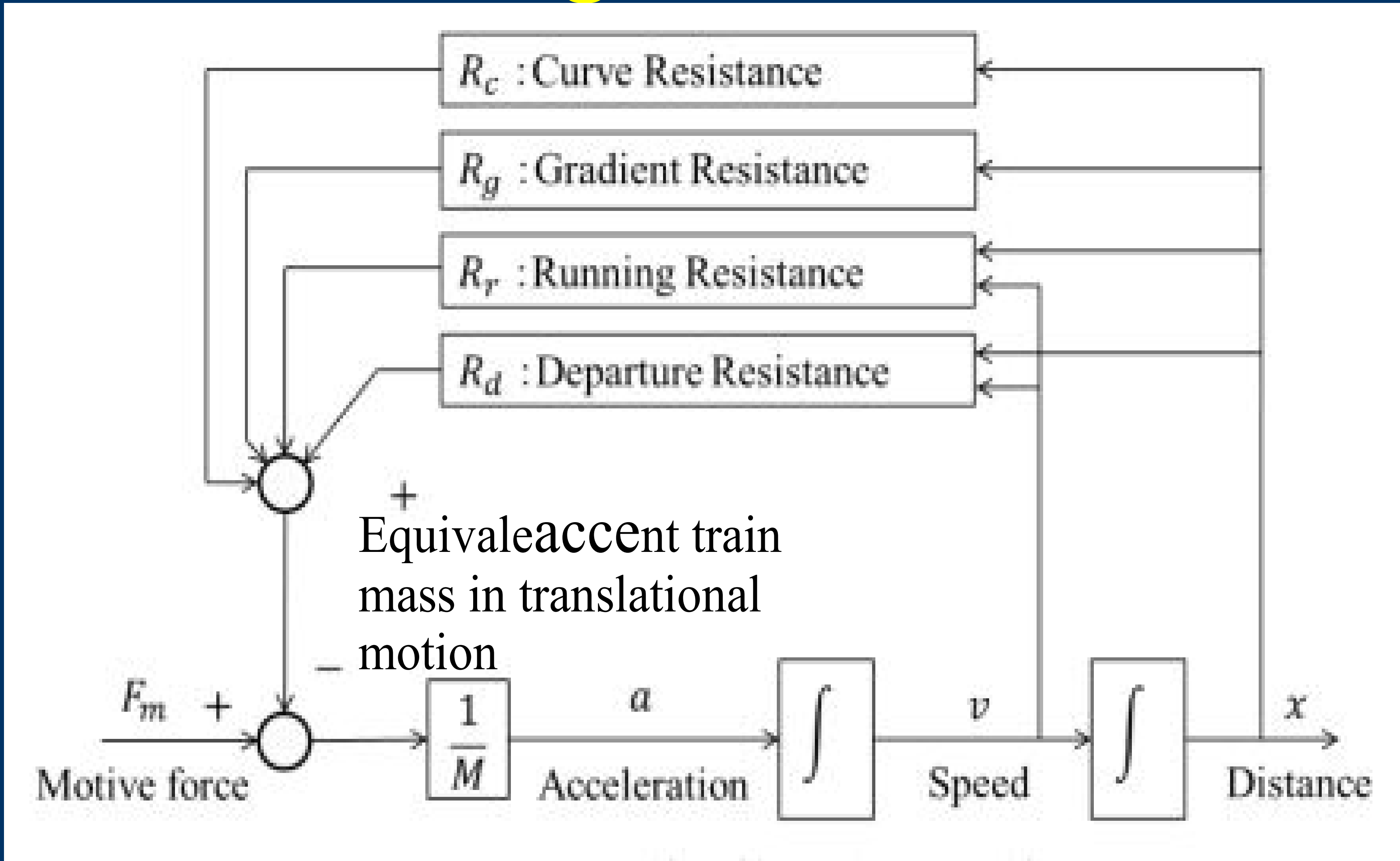


Traction curve of a LIM



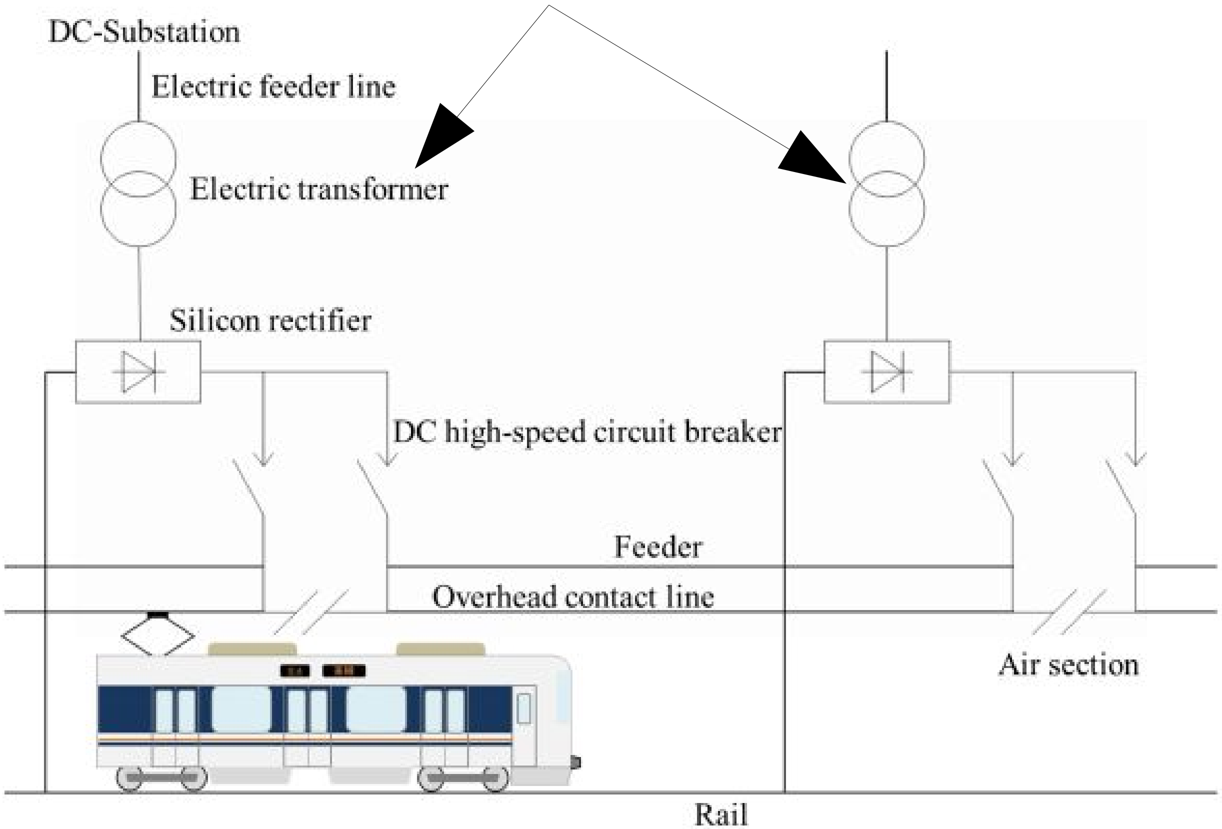


Block diagram for numerically calculating a train motion



Circuit configuration of DC-power supply for calculating change of pantograph voltage

Relatively large power demand other than traction is expected in many subway systems. Therefore, there are also regenrative power converters in many substations in subways.



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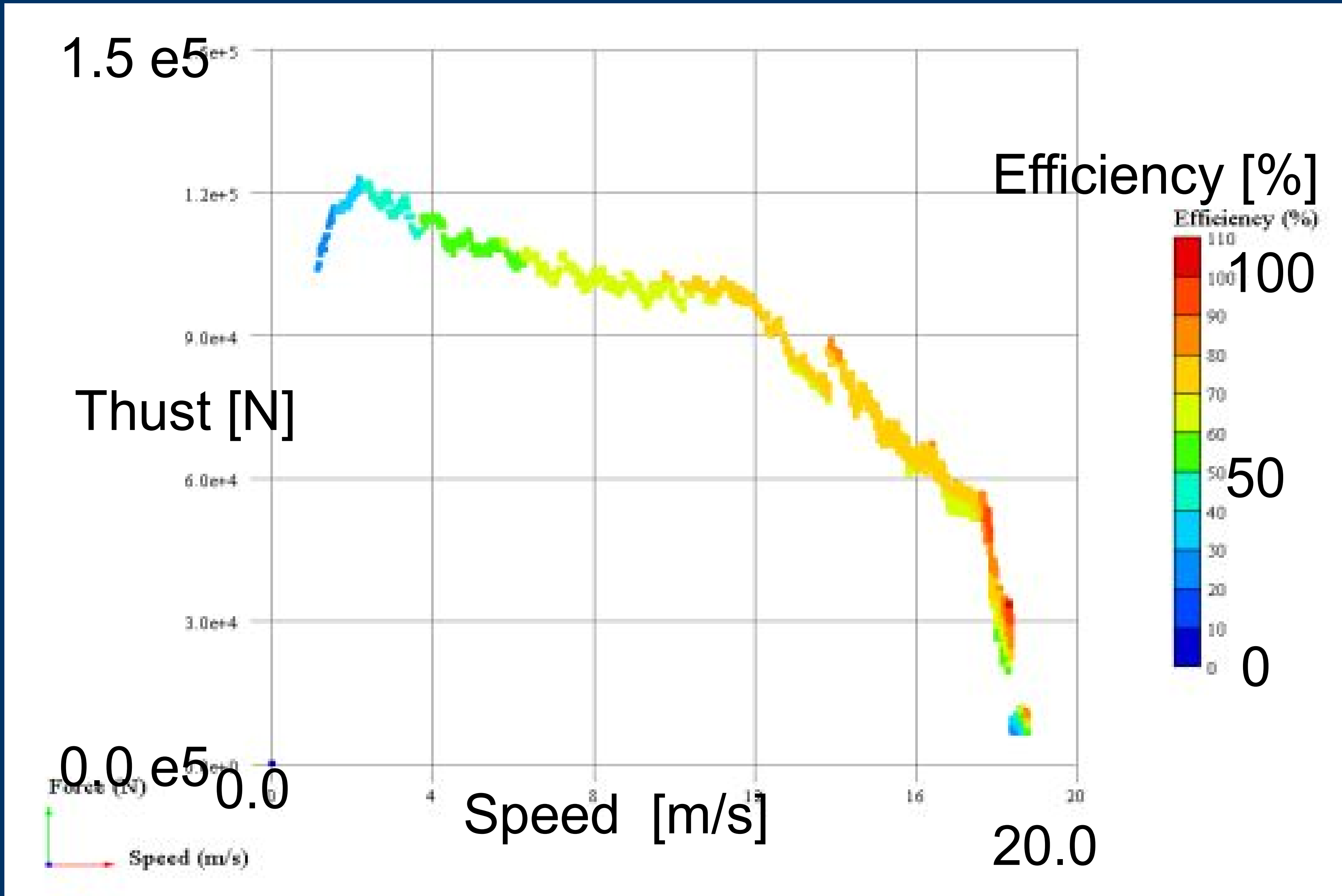
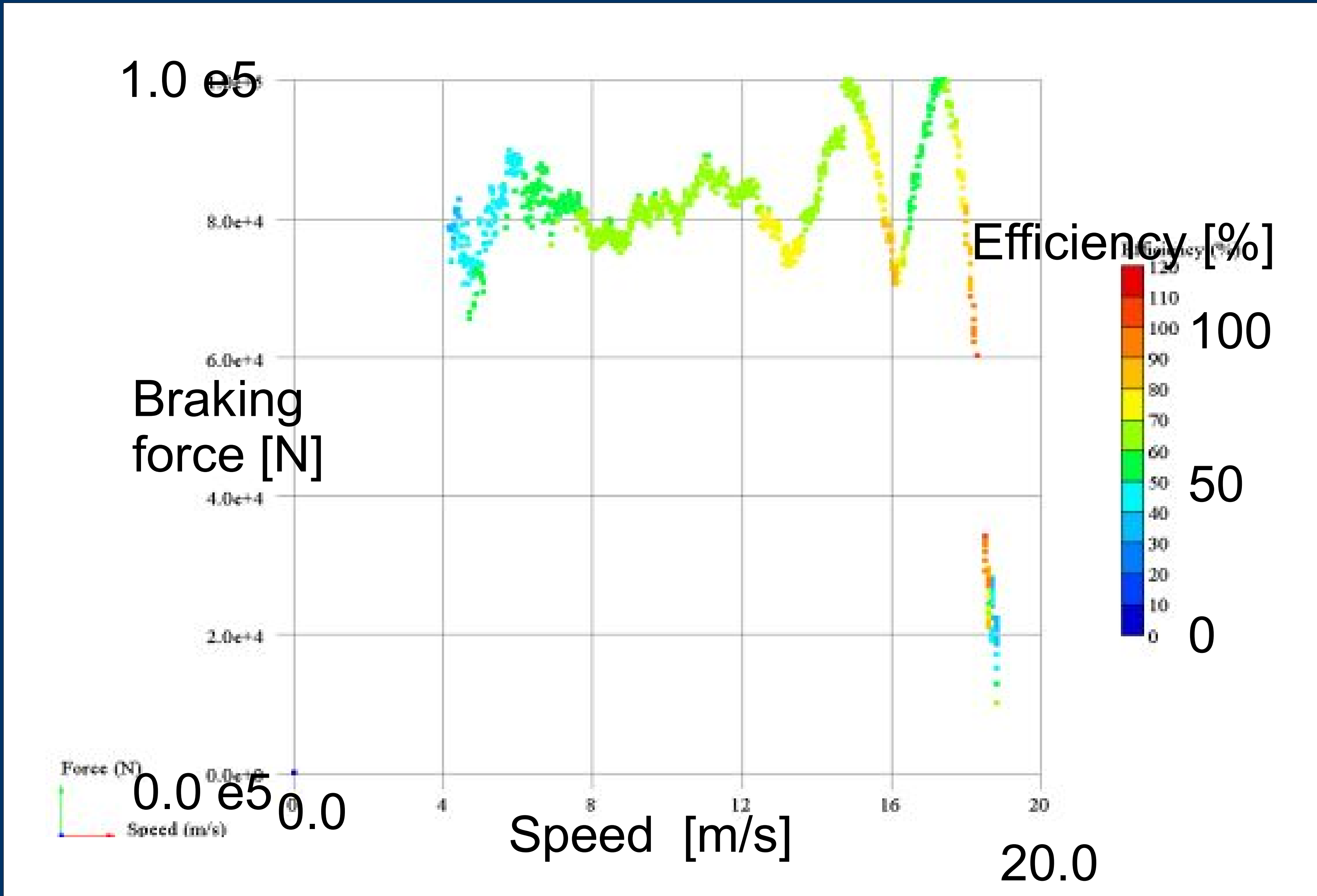
Efficiency map in powering mode

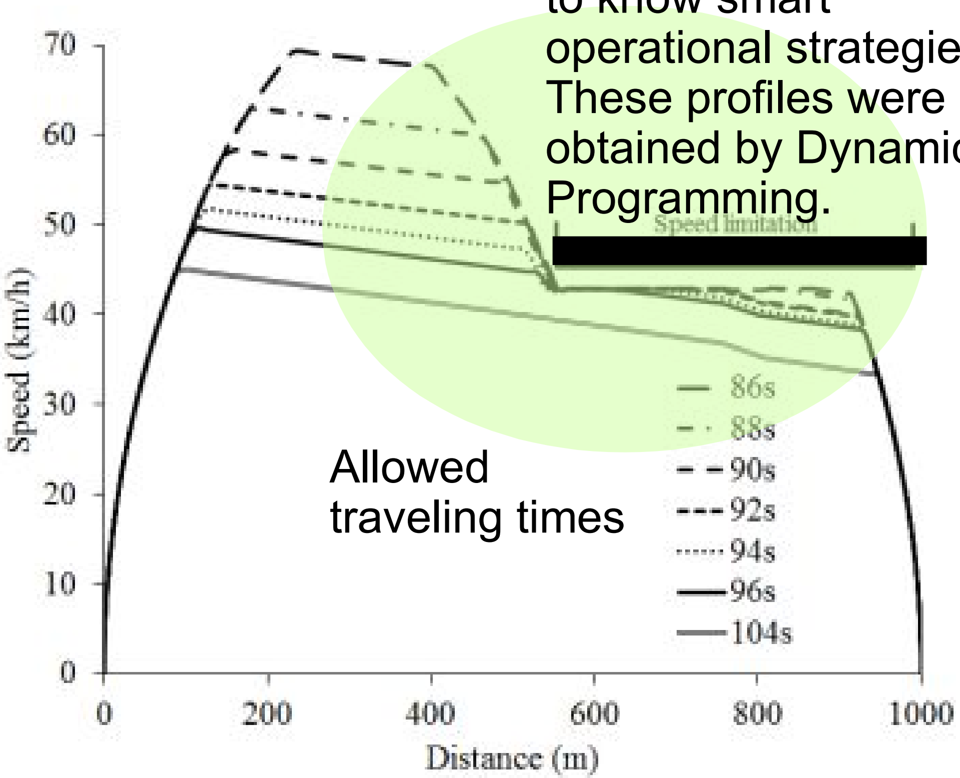


Efficiency map in braking mode



An example of train-running profiles
under sectional inequality constraints in speed numerically optimized by dynamic programming

Under such complicated sectional speed-constraints, numerical optimization is a powerful measure to know smart operational strategies. These profiles were obtained by Dynamic Programming.

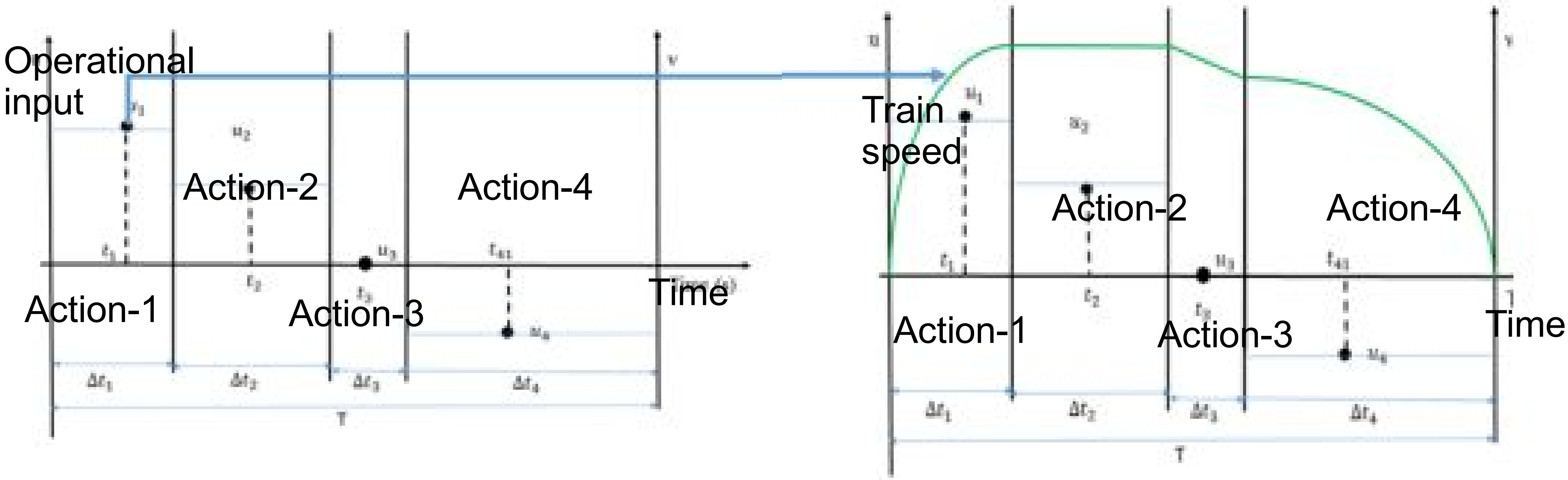


New theory

for energy-saving effort

Optimization for difficult cases

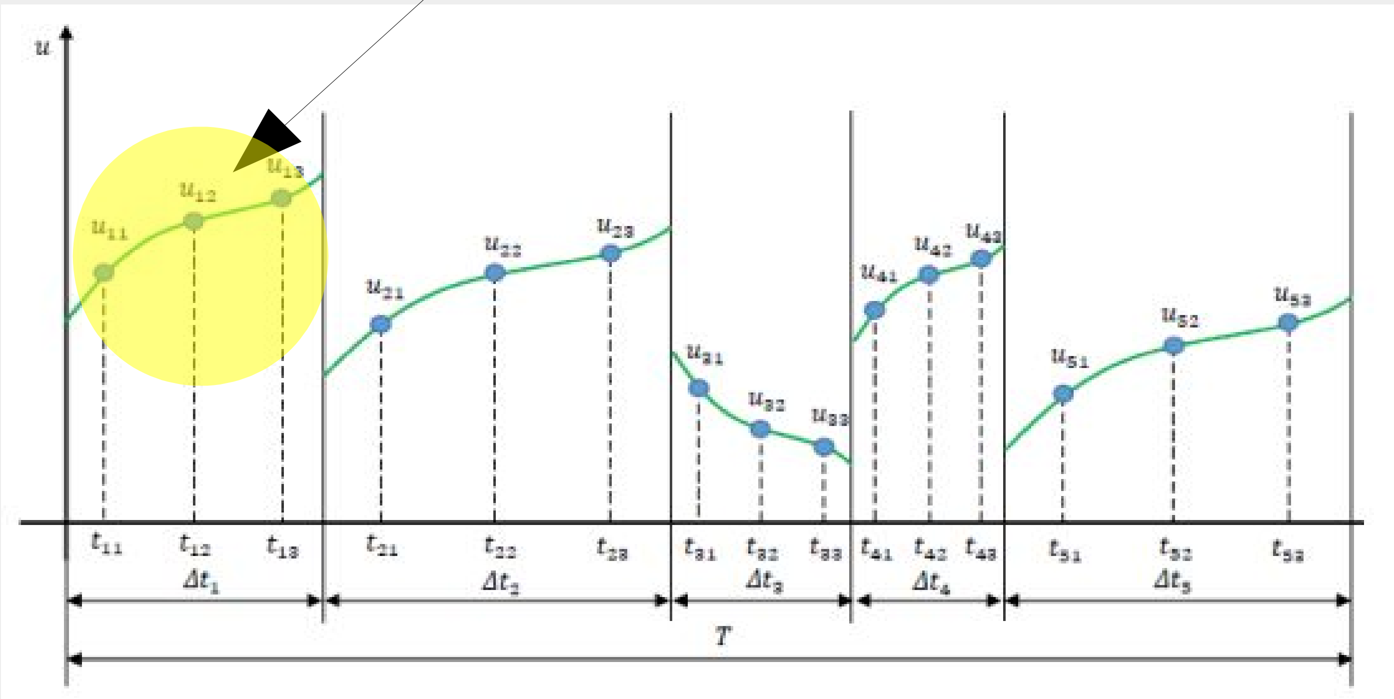
Fundamental modeling for parametric optimization of notch-input actions



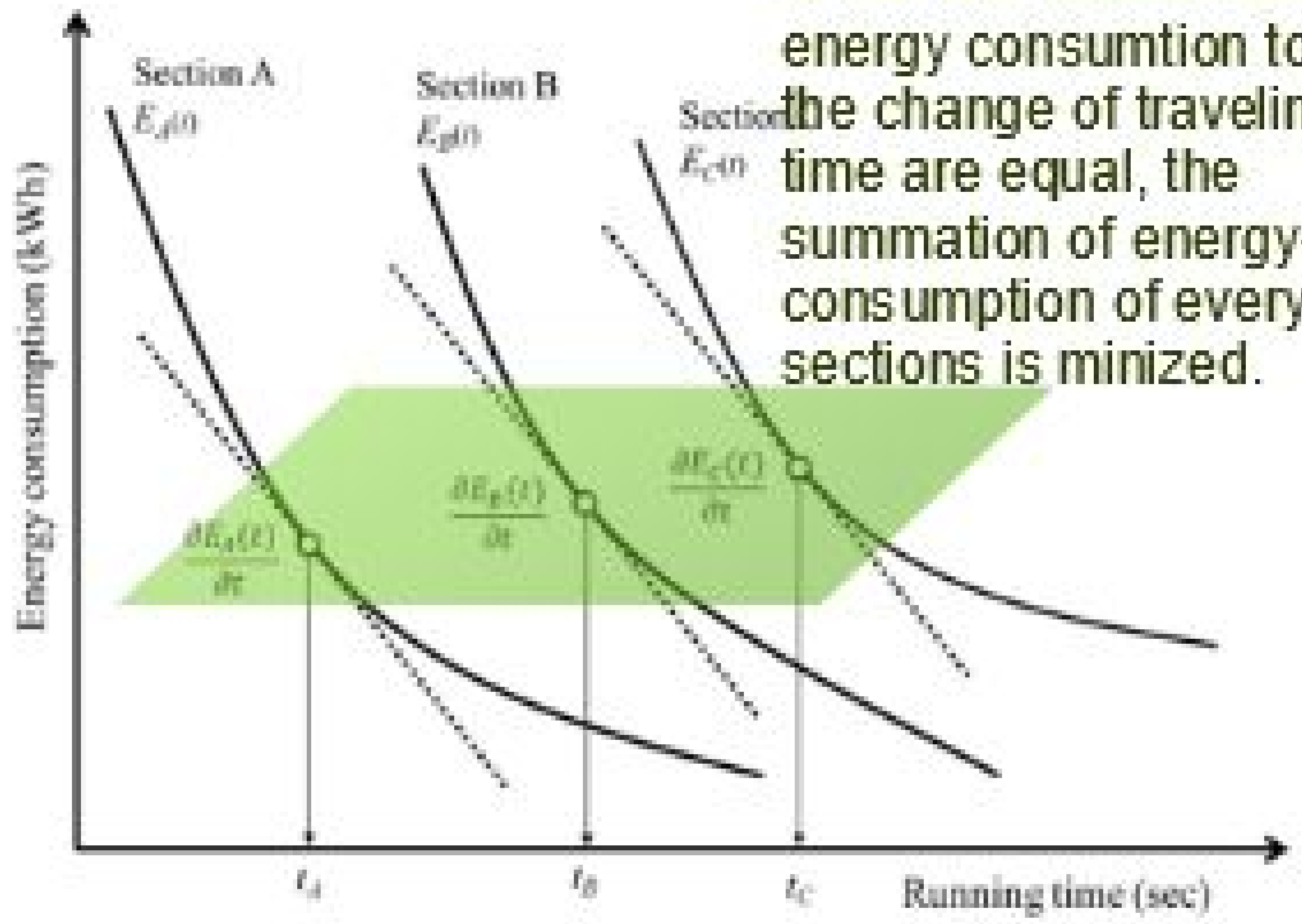
(a) Operational input level (b) Resultant speed profile

Parametric optimization of notch-input actions

If the input actions are requeted to be continuous, each actoin may be aproximated as polynomials. For instance, when each input action is approximated as the second-oreder polynomial, the amount of the input are represented three points per action as illlustrated in this figure.



Energy-Time chart and equal sensitivity condition for total minimal energy consumption

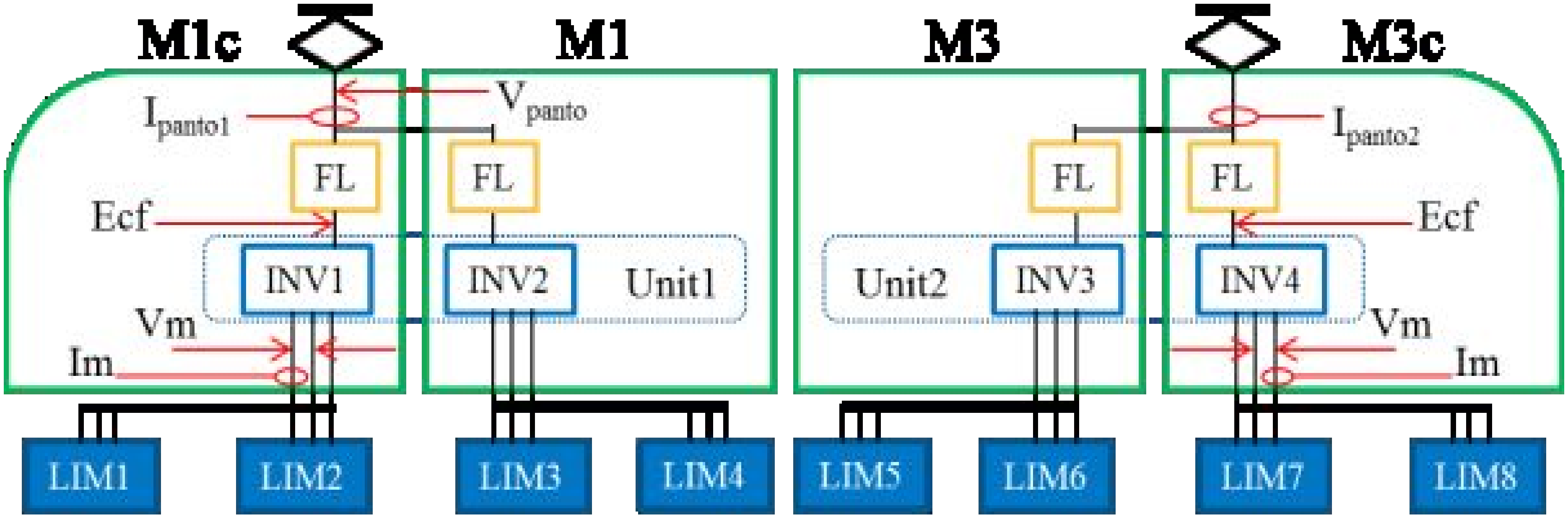


When the sensitivites of energy consumtion to the change of traveling time are equal, the summation of energy-consumption of every sections is minized.

Experimental verification

Vehicle test on a commercial track in 2015

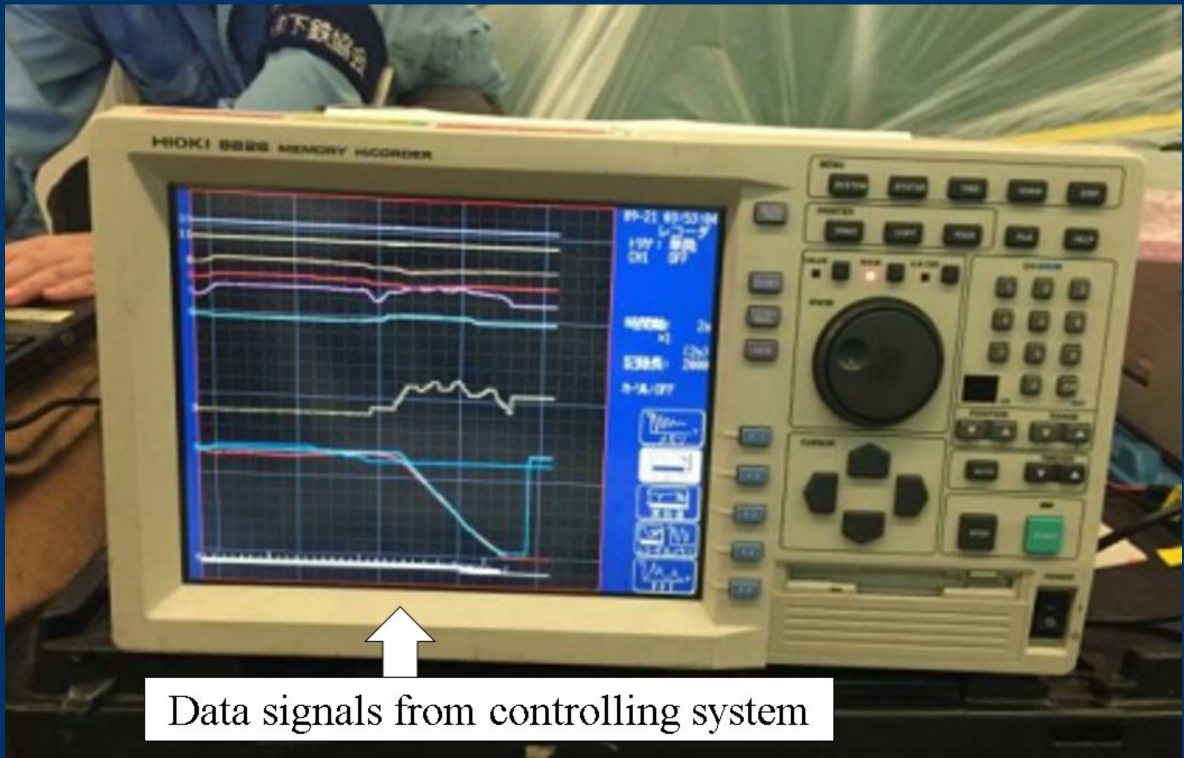
Vehicle tests in 2015



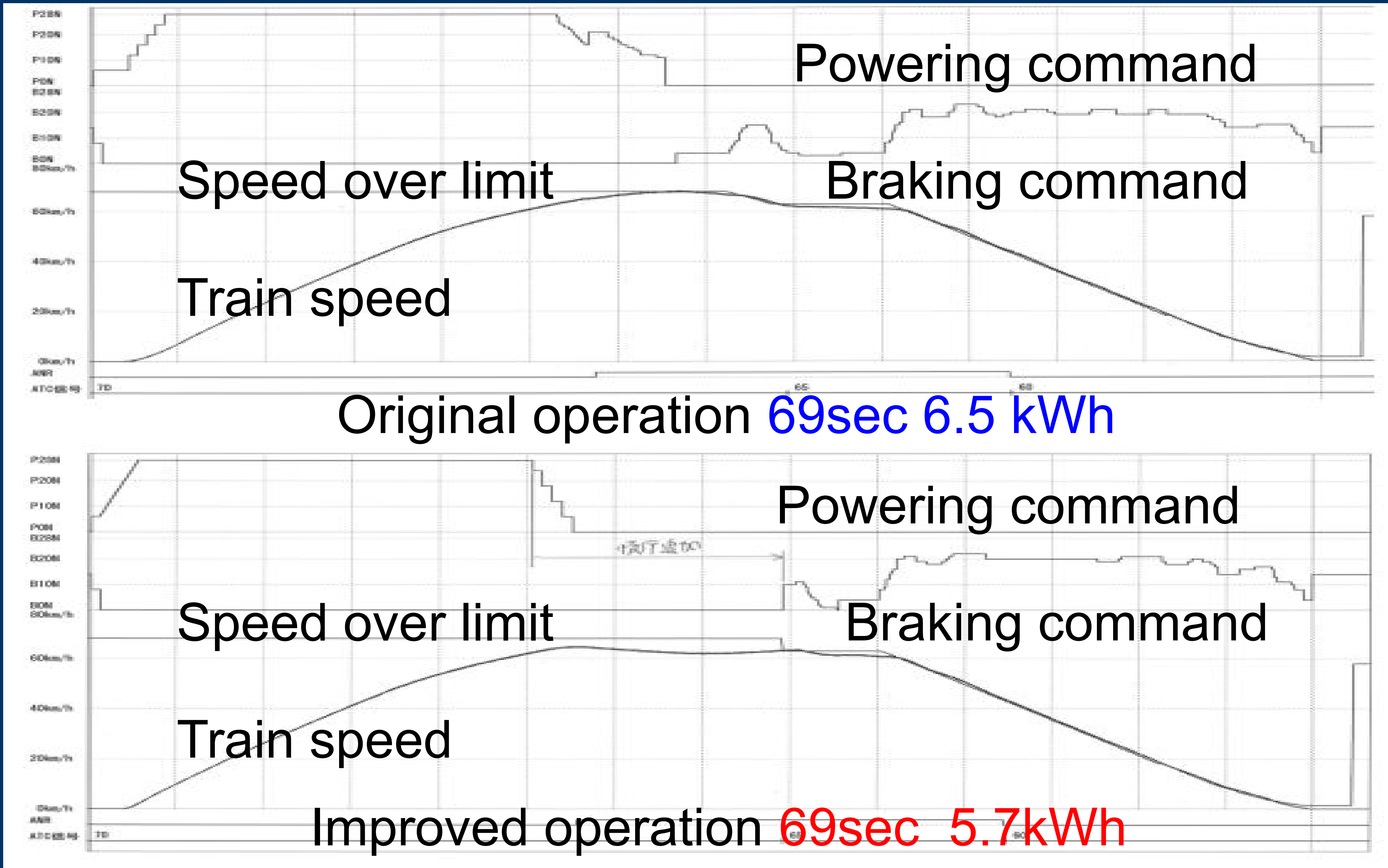
What to be measured in the vehicle tests?

Vehicle tests in 2015

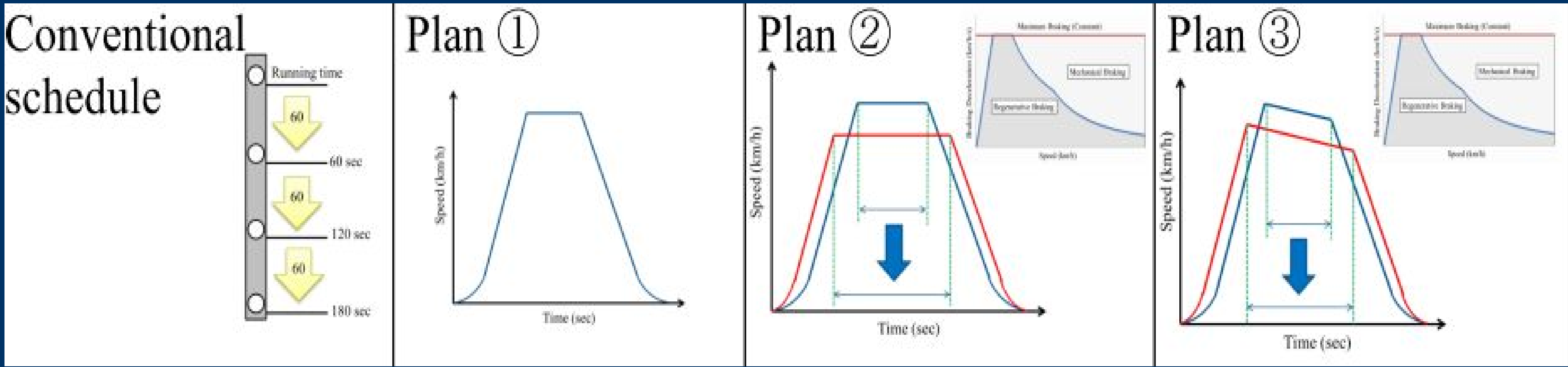
Dr. Watanabe's works with JSA

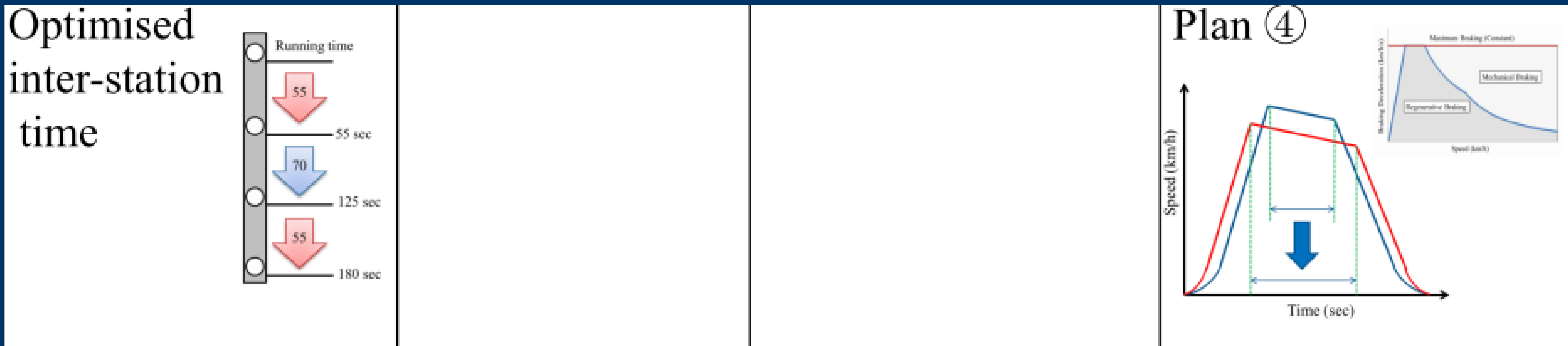


Example of operation improvement



Steps of operation improvement

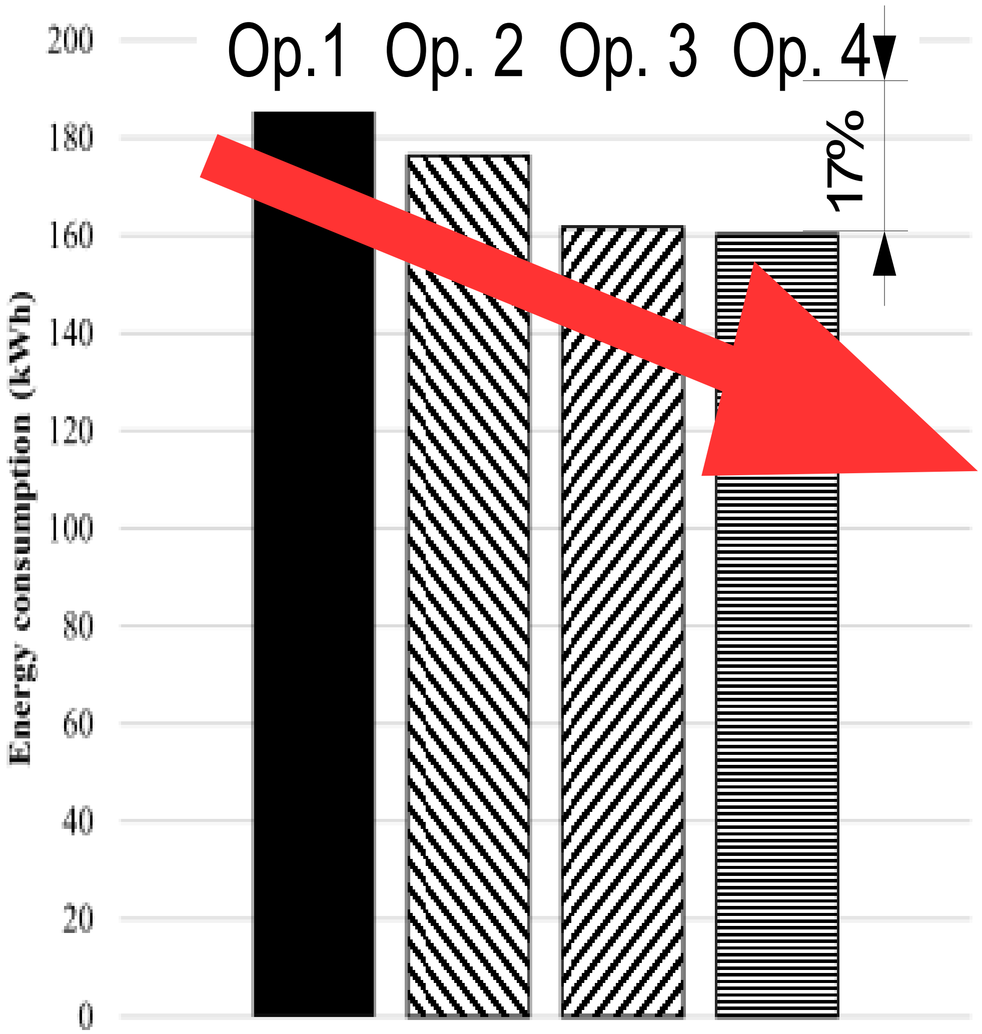




Examples of **energy-saving effect** at a couple of inter-station sections

	Plan 1		Plan 3		Time difference (sec)	Energy-Saving ratio
	Running time (sec)	Energy Consumption (kWh)	Running time (sec)	Energy Consumption (kWh)		
Section A	58	5.67	58	4.87	±0	14.1%
Section B	71	6.18	71	5.41	±0	12.5%
Section C	69	6.54	69	5.69	±0	13.0%

Summary of final achievement of our energy-saving efforts



Final comparison among thefollowing four cases:
Op.1: conventional operation,
Op. 2: operation with best use of regenerative braking and efficient notch selection supported by time margin "dug-out" by reduction of jerk-controltimes,
Op. 3: operation with introductionof possibly long coasting modes addional to Op. 2, and
Op. 4: operation with inter-station traveling time optimization explained in Fig. 12 additonal to Op. 3.

Conclusions

1) Successful challenge to design **energy-efficient ATO for linear metros** **by w**orking group at JSA from 2012 through 2015.

2) The ATO for the best use of regenerative brakes and coasting at high speed: **Energy-reduction of more than 16%**.

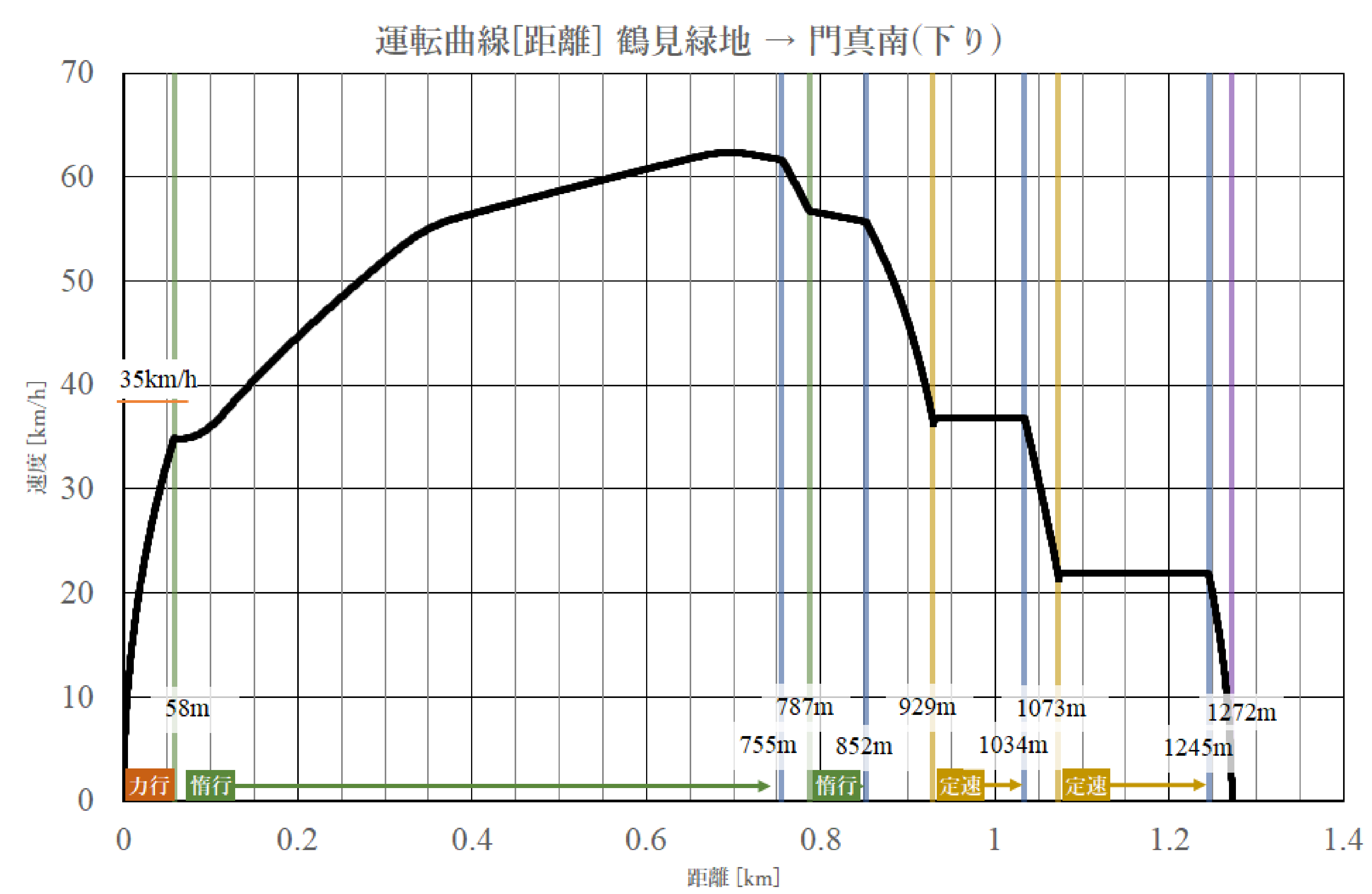
3) **Systematic slow-downs for energy-saving**, if slight increase of traveling time were allowed.

4) Future work I: More advanced power management using **wayside/onboard energy storage**

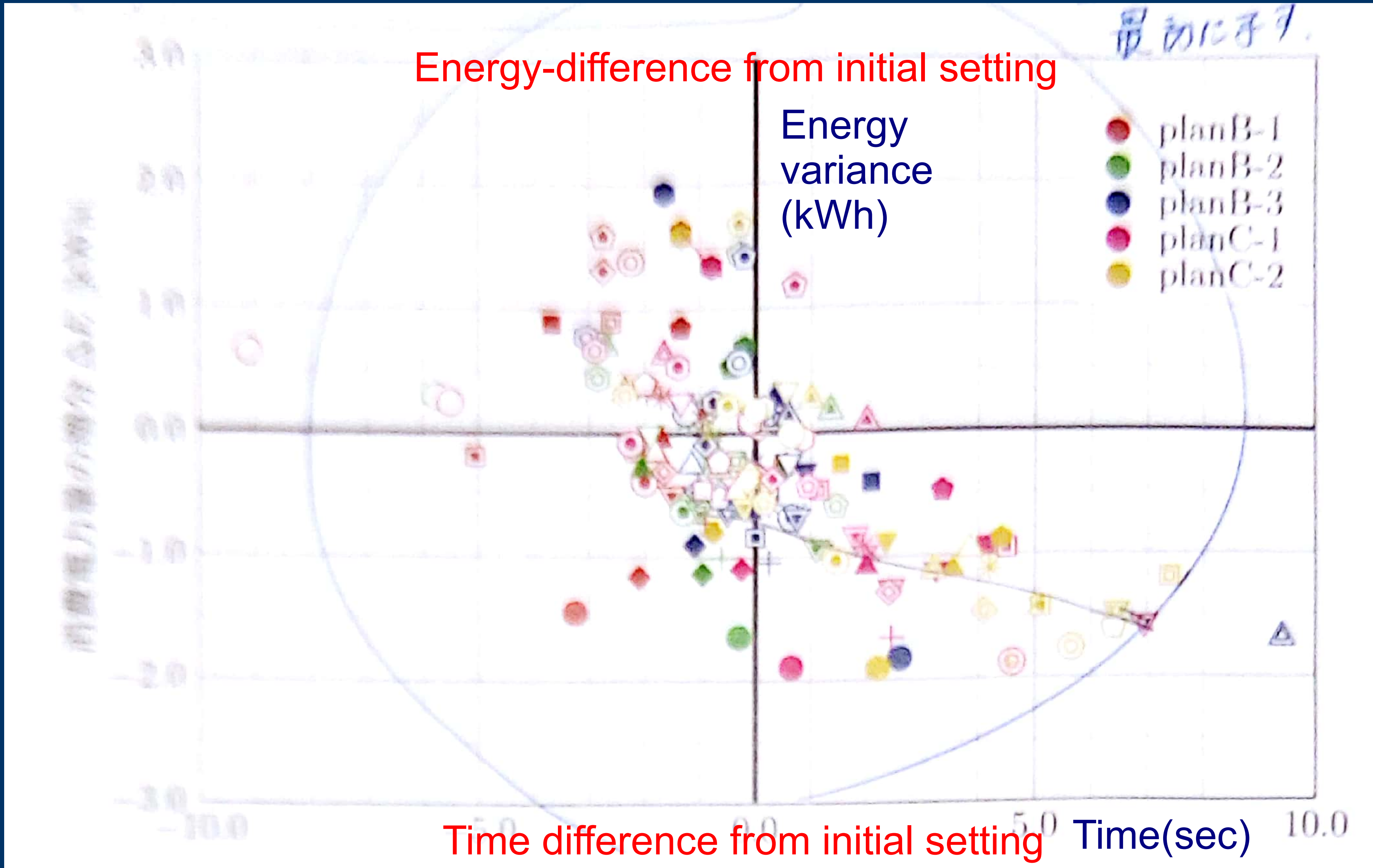
5) Future work II: Comprehensive **implementation** of this efficient ATO *under working*

Appendix: further application in 2017

Appendix: further application in 2017



Appendix: further application in 2017 (Working document)



Appendix: further application in 2017 (Working document)