

Fundamental Research on Range Extension Autonomous Driving for Electric Vehicles Based on Optimization of Vehicle Velocity Profile in Consideration of Cornering

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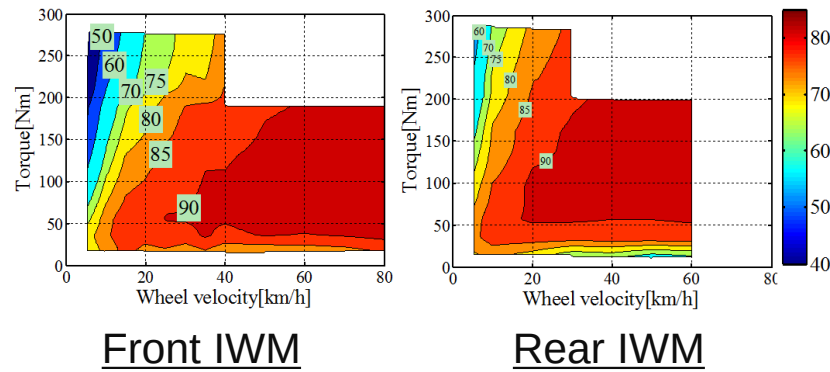
1. Background
2. Vehicle Model
3. Range Extension Autonomous Driving
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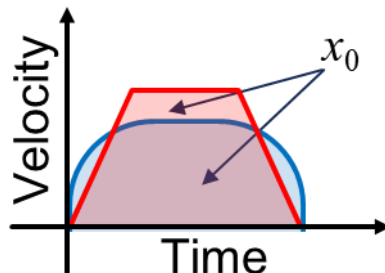
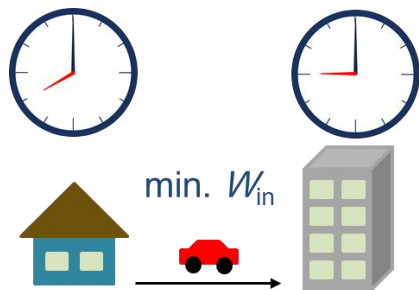
■ 1.1 Background

Advantage of Electric Vehicles

- Environmental performance
- High controllability of electric motor



Efficiency maps



Disadvantage of Electric Vehicles

- Miles-per-charge is shorter than range of ICEVs



Range Extension Control System

- Torque is distributed to each wheel to minimize instantaneous power [H. Fujimoto et al. IEEE TIE 2015]

Autonomous Driving

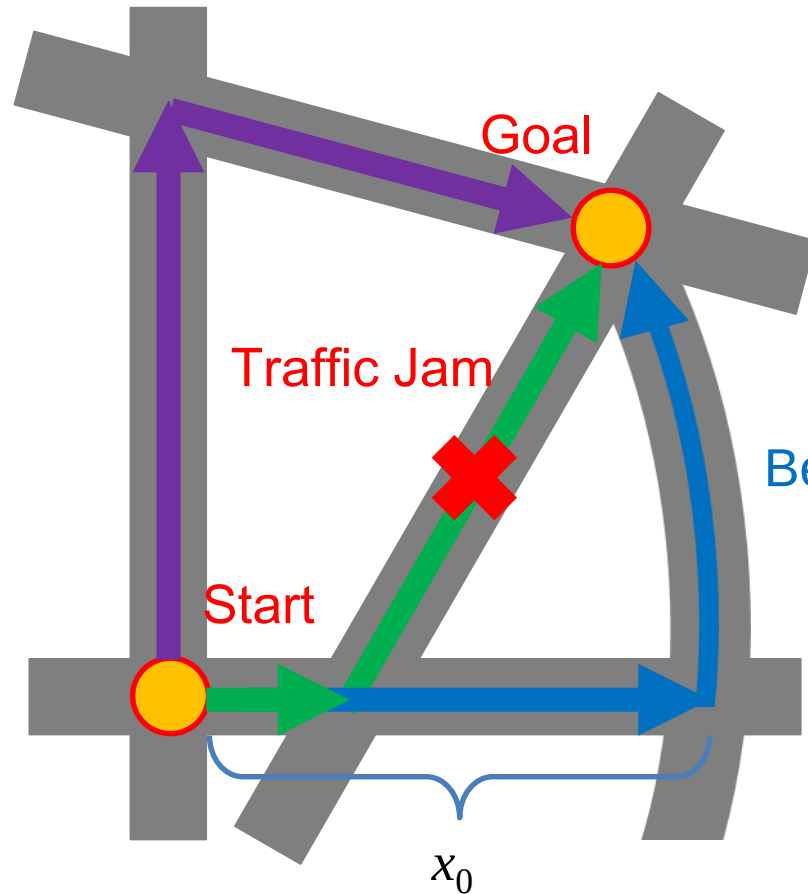


Range Extension Autonomous Driving

- Velocity profile is optimized to minimize consumption energy for autonomous vehicle [Y. Ikezawa et al. IEEEJ JIA 2016]

IEEEJ JIA 2016]

■ 1.2 Range Extension Autonomous Driving



Best !

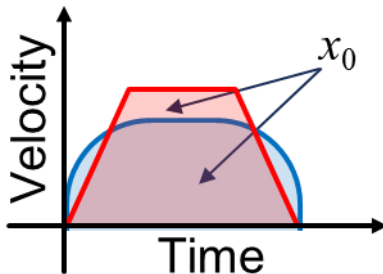
Present Navigating System

- System gets some route leading to destination and traffic congestion information
- System proposes us optimal route



Range Extension Autonomous Driving

- System divides a route into some segments
- System generates optimal velocity profile for each segment to minimize consumption energy

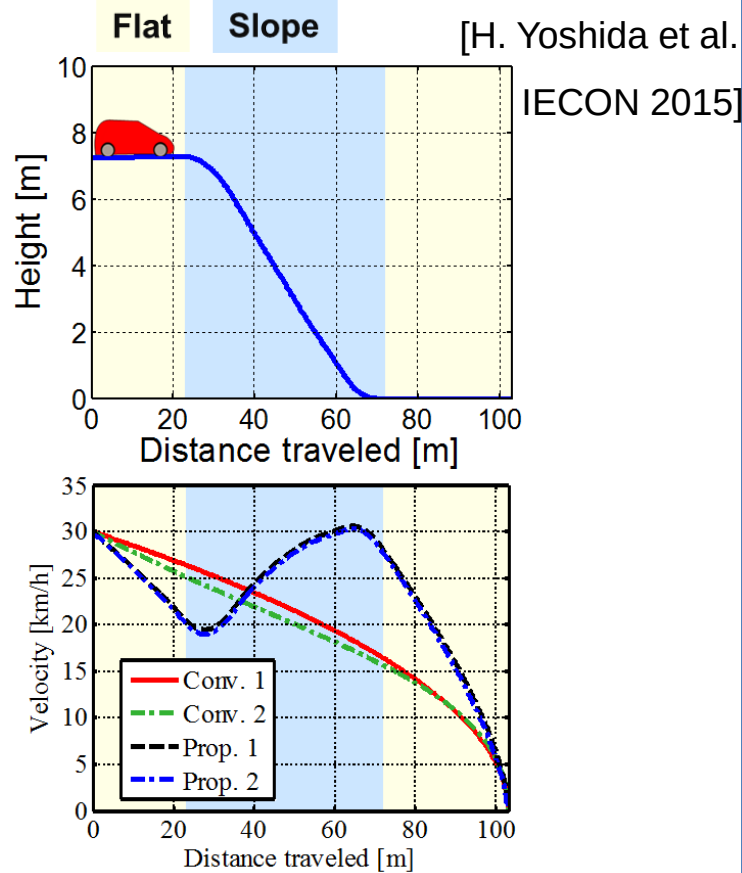


Assumption

- Anterior state (following distance, road shape information, ...) can be gotten by ITS

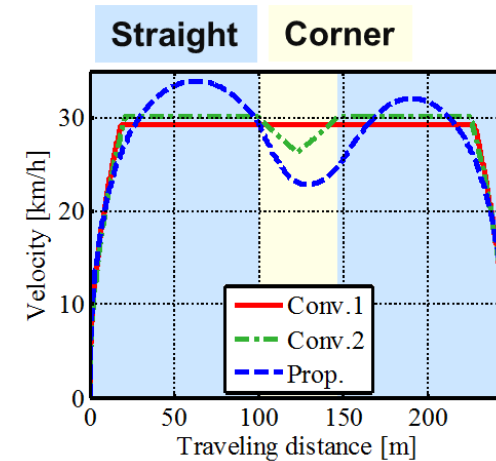
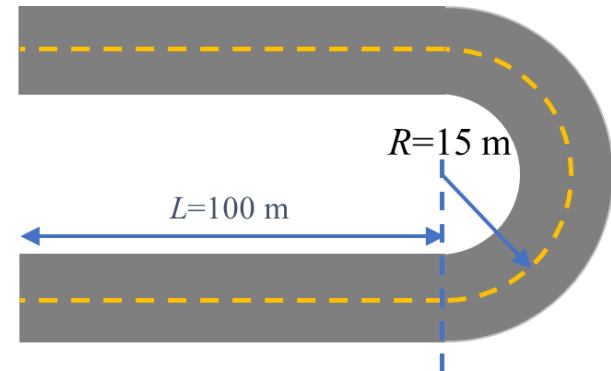
1.3 Range Extension Autonomous Driving

Previous Research



- Consumption energy is minimized by optimizing velocity profile in consideration of **straight road** including road gradient

This Research



- Consumption energy is minimized by optimizing velocity profile in consideration of **cornering**



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1. Background

2. Vehicle Model

3. Range Extension Autonomous Driving

4. Simulation

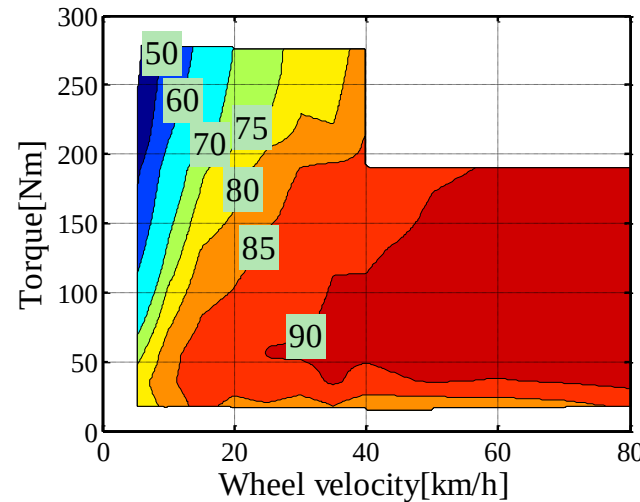
5. Experiment

6. Conclusion

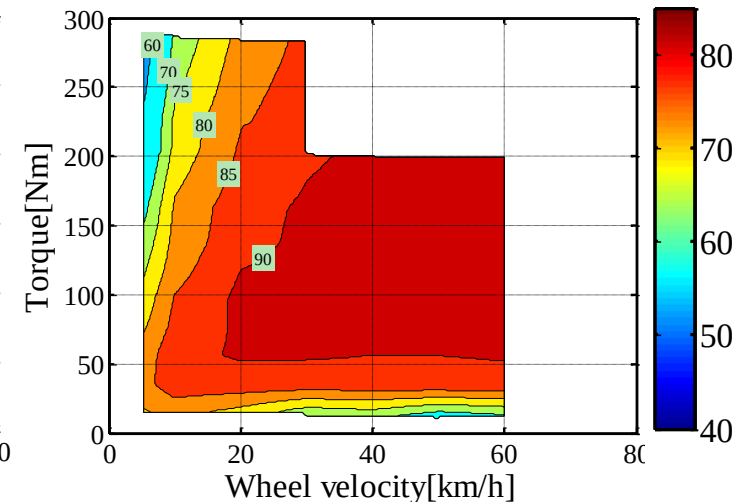
■ 2.1 Experimental Vehicle



FPEV2-Kanon



Front motor



Rear motor

Efficiency maps of front and rear motor

Characteristic

- In-wheel motor, manufactured by TOYO DENKI SEIZO K.K., installed in each wheel
- Motors can be independently controlled
- Direct-drive
- Motor efficiencies are different in front and rear

Specification of in-wheel motors

	Front	Rear
Rated torque	100 N	127 Nm
Maximum torque	500 Nm	530 Nm
Rated power	6.00 kW	6.00 kW
Maximum power	20.0 kW	25.0 kW
Rated speed	382 rpm	450 rpm
Maximum speed	1110 rpm	1200 rpm

■ 2.2 Vehicle Dynamics

Longitudinal direction

$$M\dot{V} = F_{\text{all}} - Mgsin\theta - \text{sgn}(V)(F_{\text{DR}} + F_{\text{CR}})$$

Lateral direction

$$\begin{aligned} Ma_y &= MV(\dot{\beta} + \gamma) \\ &= -2Y_f - 2Y_r \end{aligned}$$

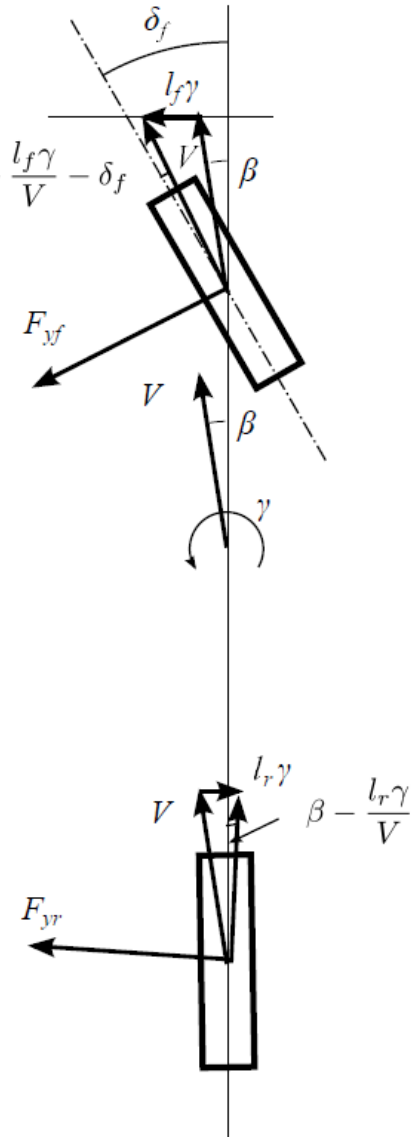
Yaw direction

$$I\dot{\gamma} = 2(-l_f Y_f + l_r Y_r)$$

Tyre slip angle

$$\begin{aligned} \alpha_f(V, \beta, \gamma, \delta_f) &= \beta + \frac{l_f \gamma}{V} - \delta_f \\ \alpha_r(V, \beta, \gamma) &= \beta - \frac{l_r \gamma}{V} \end{aligned}$$

F_{all}	Total driving force
F_{DR}	Driving resistance
F_{CR}	Cornering resistance
β	Side slip angle
γ	Yaw rate
Y_f, Y_r	Lateral force



Bicycle model

■ 2.3 Cornering Resistance

Cornering Force

$$F_{yf} = -C_f \alpha_f$$

$$F_{yr} = -C_r \alpha_r$$

Lateral Force of Tyre

$$Y_f \simeq F_{yf}$$

$$Y_r \simeq F_{yr}$$

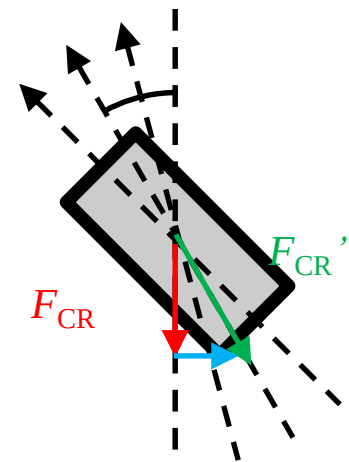
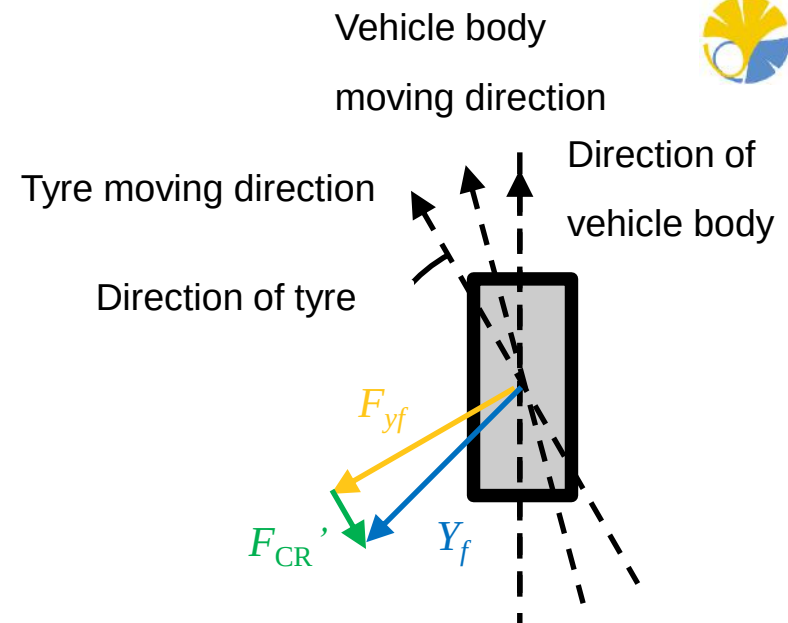
Traveling direction component force of Lateral Force

$$\begin{aligned} F_{CR}' &\simeq -2Y_f \sin \alpha_f - 2Y_r \sin \alpha_r \\ &\simeq 2C_f \alpha_f^2 + 2C_r \alpha_r^2 \end{aligned}$$

x-direction component force of F_{CR}'

$$\begin{aligned} F_{CR} &\simeq 2C_f \alpha_f^2 \cos \delta_f + 2C_r \alpha_r^2 \\ &\simeq 2C_f \alpha_f^2 + 2C_r \alpha_r^2 \end{aligned}$$

Cornering resistance is proportional to square of tyre slip angle



■ 2.4 Approximation of Tyre Slip Angle

$$\dot{x} = Ax + Bu$$

$$A = \begin{pmatrix} -\frac{2(C_f + C_r)}{MV} & -\frac{2(l_f C_f - l_r C_r)}{MV^2} - 1 \\ -\frac{2(l_f C_f + l_r C_r)}{I} & -\frac{2(l_f^2 C_f + l_r^2 C_r)}{IV} \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{2C_f}{MV} \\ \frac{2l_f C_f}{I} \end{pmatrix}$$

$$x = \begin{pmatrix} \beta \\ \gamma \end{pmatrix}$$

$$u = \delta_f$$

If vehicle is brought into stationary circular turn ($\dot{\beta} = 0, \dot{\gamma} = 0$)...

$$\beta = (1 - BV^2) \frac{l}{R}$$

$$\gamma = \frac{V}{R}$$

$$\delta_f = (1 + AV^2) \frac{l}{R}$$

$$\alpha_f = -AV^2 \frac{l}{R} - BV^2 \frac{l_r}{R}$$

$$\alpha_r = -BV^2 \frac{l_r}{R}$$

$$A = -\frac{M}{2l^2} \frac{l_f C_f - l_r C_r}{C_f C_r}$$

$$B = \frac{M}{2l} \frac{l_f}{l_r C_r}$$

■ 2.5 Longitudinal Equation of Motion

$$Ma_x = F_{\text{all}} - \text{sgn}(V)(\boxed{F_{\text{DR}}} + \boxed{F_{\text{CR}}})$$

$$\boxed{F_{\text{DR}}} = \mu_0 Mg + b\boxed{V} + \frac{1}{2}\rho C_d S\boxed{V^2}$$

Driving resistance

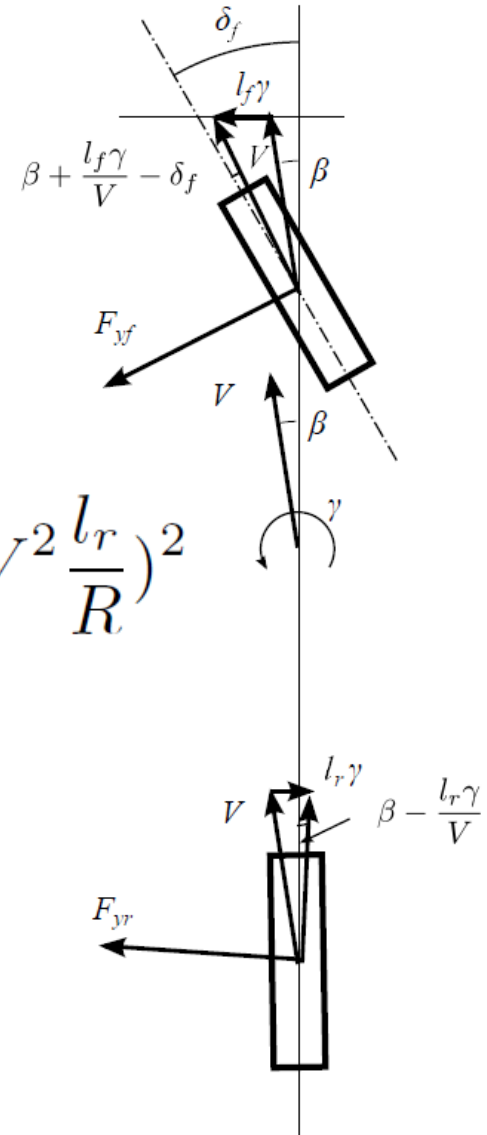
$$\boxed{F_{\text{CR}}} = 2C_f \left(AV^2 \frac{l}{R} + BV^2 \frac{l_r}{R} \right)^2 + 2C_r \left(BV^2 \frac{l_r}{R} \right)^2$$

Cornering resistance

$$= \frac{M^2}{2l^2} \left(\frac{l_r^2}{C_f} + \frac{l_f^2}{C_r} \right) \boxed{V^4}$$

Equal Distribution

$$F_f = F_r = \frac{1}{4} F_{\text{all}}$$



Bicycle model

■ 2.6 Inverter Input Power

Inverter input power

$$P_{in} = P_{out} + P_c + P_i$$

Mechanical output

$$P_{out} = 2 \sum_{j=f,r} \omega_j T_j$$

$$\simeq \frac{VF_{all}}{2} \sum_{j=f,r} \left(1 + \frac{F_{all}}{4D_s' N_j(V, F_{all})} \right)$$

Copper loss

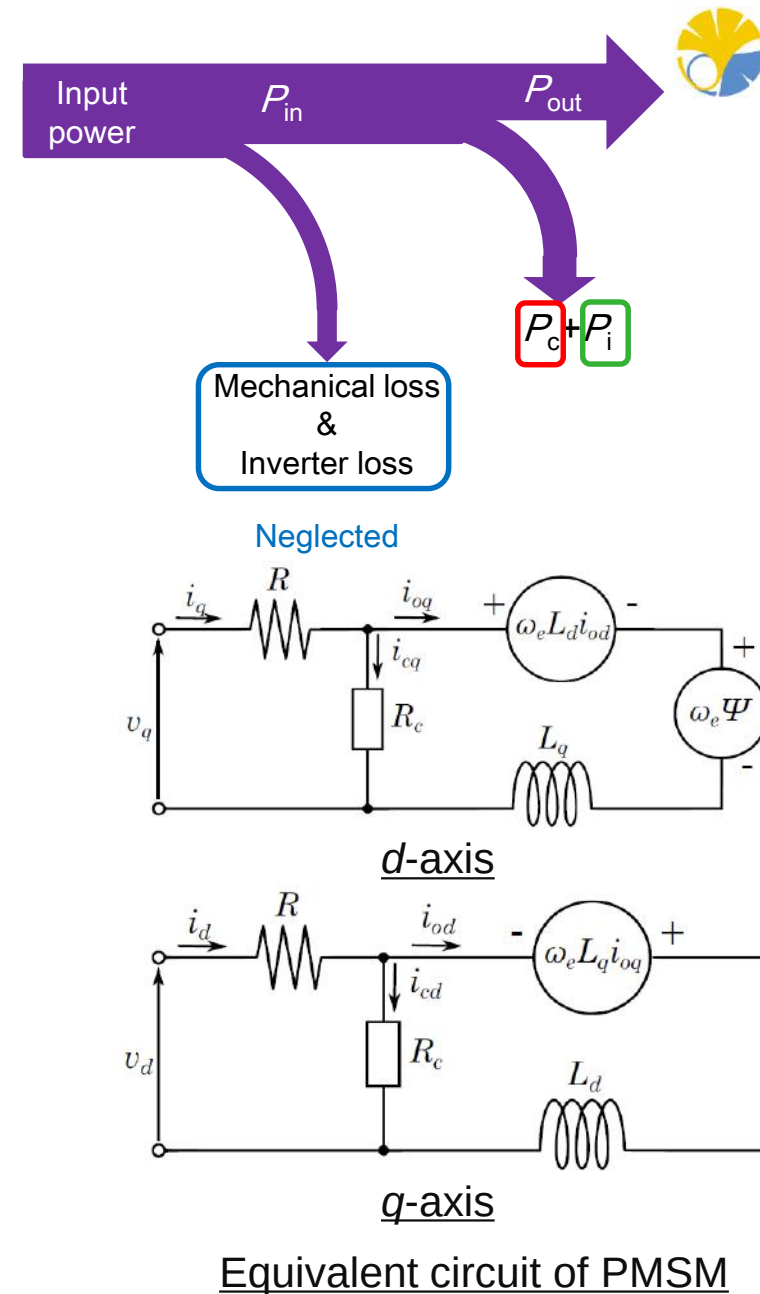
$$P_c = 2 \sum_{j=f,r} R_j i_{qj}^2$$

$$\simeq \frac{r^2}{8} F_{all}^2 \sum_{j=f,r} \frac{R_j}{K_{tj}^2}$$

Iron loss

$$P_i = 2 \sum_{j=f,r} \frac{v_{odj}^2 + v_{ojq}^2}{R_{cj}}$$

$$\simeq 2 \frac{V^2}{r^2} \sum_{j=f,r} \frac{P_{nj}^2}{R_{cj}} \left\{ \left(\frac{r L_{qj} F_{all}}{4 K_{tj}} \right)^2 + \Psi_j^2 \right\}$$





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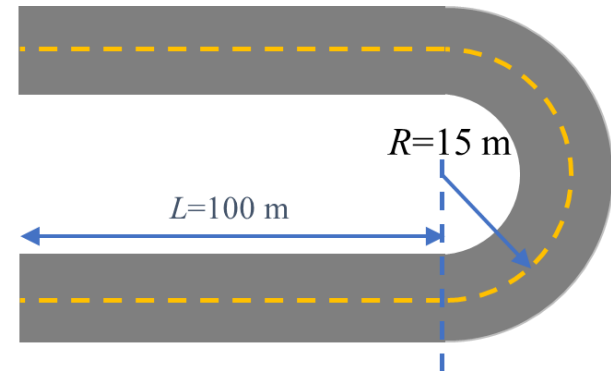
■ 3. Range Extension Autonomous Driving

$$\begin{aligned}
 \text{min.} \quad & W_{\text{in}} = \int_{t_0}^{t_f} P_{\text{in}}(\mathbf{x}(t), \mathbf{u}(t)) dt \\
 \text{s.t.} \quad & \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) \\
 & = \begin{bmatrix} \frac{1}{M} [F_{\text{all}} - \text{sgn}(V)(F_{\text{DR}}(V) + F_{\text{CR}}(V, R))] \\ V(t) \\ -\frac{2(C_f + C_r)}{MV} \beta - \left[\frac{2(l_f C_f - l_r C_r)}{MV^2} - 1 \right] \gamma + \frac{2C_f}{MV} \delta_f \\ -\frac{2(l_f C_f + l_r C_r)}{I} \beta - \frac{2(l_f^2 C_f + l_r^2 C_r)}{IV} \gamma + \frac{2l_f C_f}{I} \delta_f \end{bmatrix}
 \end{aligned}$$

$$\chi(\mathbf{x}(t_0)) = \mathbf{x}(t_0) - \mathbf{x}_0 = \mathbf{0}$$

$$\psi(\mathbf{x}(t_f)) = \mathbf{x}(t_f) - \mathbf{x}_f = \mathbf{0}$$

$$\mathbf{x}(t) = \begin{bmatrix} V(t) \\ X(t) \\ \beta(t) \\ \gamma(t) \end{bmatrix} \quad \mathbf{u}(t) = \begin{bmatrix} F_{\text{all}}(t) \\ \delta_f(t) \end{bmatrix}$$



- $\delta_f(t)$ is treated as a function of V and R on the assumption that vehicle is brought into **stationary circular turn**
- $F_{\text{all}}(t)$ is optimized by using gradient method to satisfy **Euler Lagrange equation**



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■ 4.1 Comparison Conditions

$$t_0 = 0 \text{ s}, t_f = 35.0 \text{ s}$$

Conventional method 1

- a_x is optimized to minimize consumption energy.

$$V(t) = \begin{cases} V_0 + a_x t & (t_0 < t < t_1) \\ V_{\max} & (t_1 < t < t_2) \\ V_{\max} - a_x t & (t_2 < t < t_f) \end{cases}$$

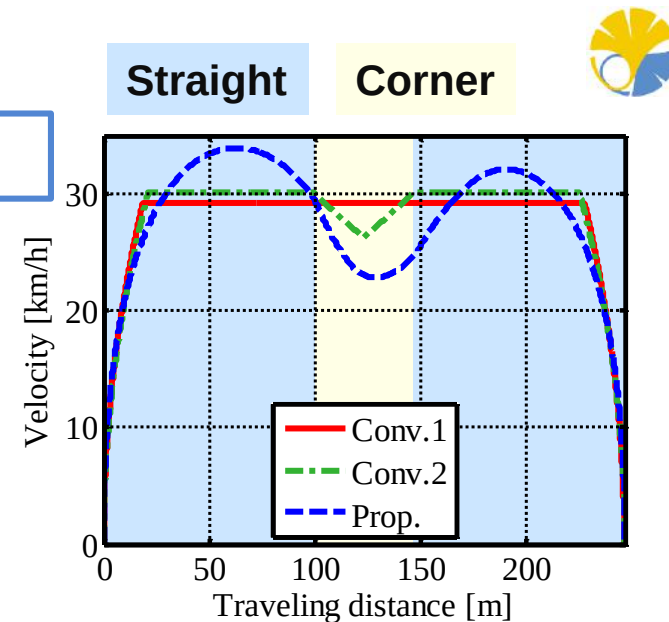
Conventional method 2

- a_x is optimized to minimize consumption energy.

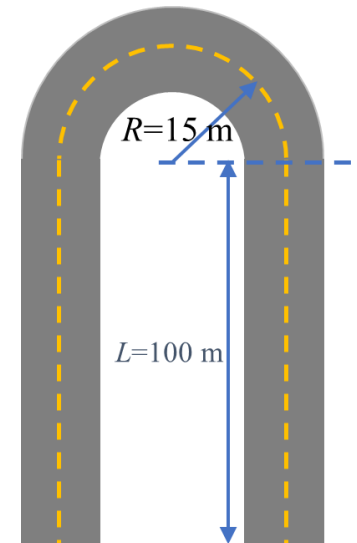
$$V(t) = \begin{cases} V_0 + a_x t & (t_0 < t < t_1) \\ V_{\max} & (t_1 < t < t_2) \\ V_{\max} - \frac{1}{M} \int_{t_2}^t (F_{\text{DR}}(V) + F_{\text{CR}}(V, R)) dt & (t_2 < t < t_3) \\ V(2t_3 - t) & (t_3 < t < t_f) \end{cases}$$

Proposed method

- The velocity profile is optimized to minimize consumption energy by solving **nonlinear optimal control problem**.



Velocity profile



Driving course



■ 4.2 Loss Separation

Mechanical output

$$P_{\text{out}} = P_M + P_J + P_{\text{DR}} + P_{\text{CR}} + P_S$$

Power stored as kinetic energy

$$P_M = \frac{d}{dt} \left(\frac{1}{2} M V^2 \right)$$

Power stored as rotational energy

$$P_J = 2 \sum_{j=f,r} \frac{d}{dt} \left(\frac{1}{2} J_{\omega_j} \omega_j^2 \right)$$

Can be recovered
during decelerating

Loss caused by driving resistance

$$P_{\text{DR}} = F_{\text{DR}} V$$

Loss caused by cornering resistance

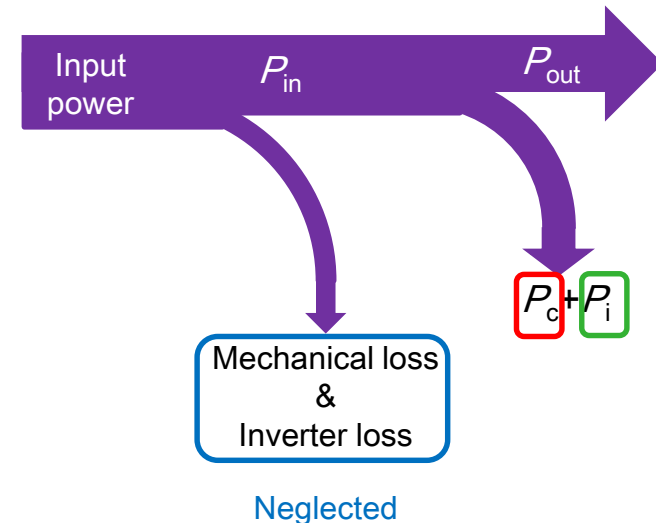
$$P_{\text{CR}} = F_{\text{CR}} V$$

Loss caused by slip

$$P_S = F_{\text{all}} V \sum_{j=f,r} \lambda_j \gamma_j(k)$$

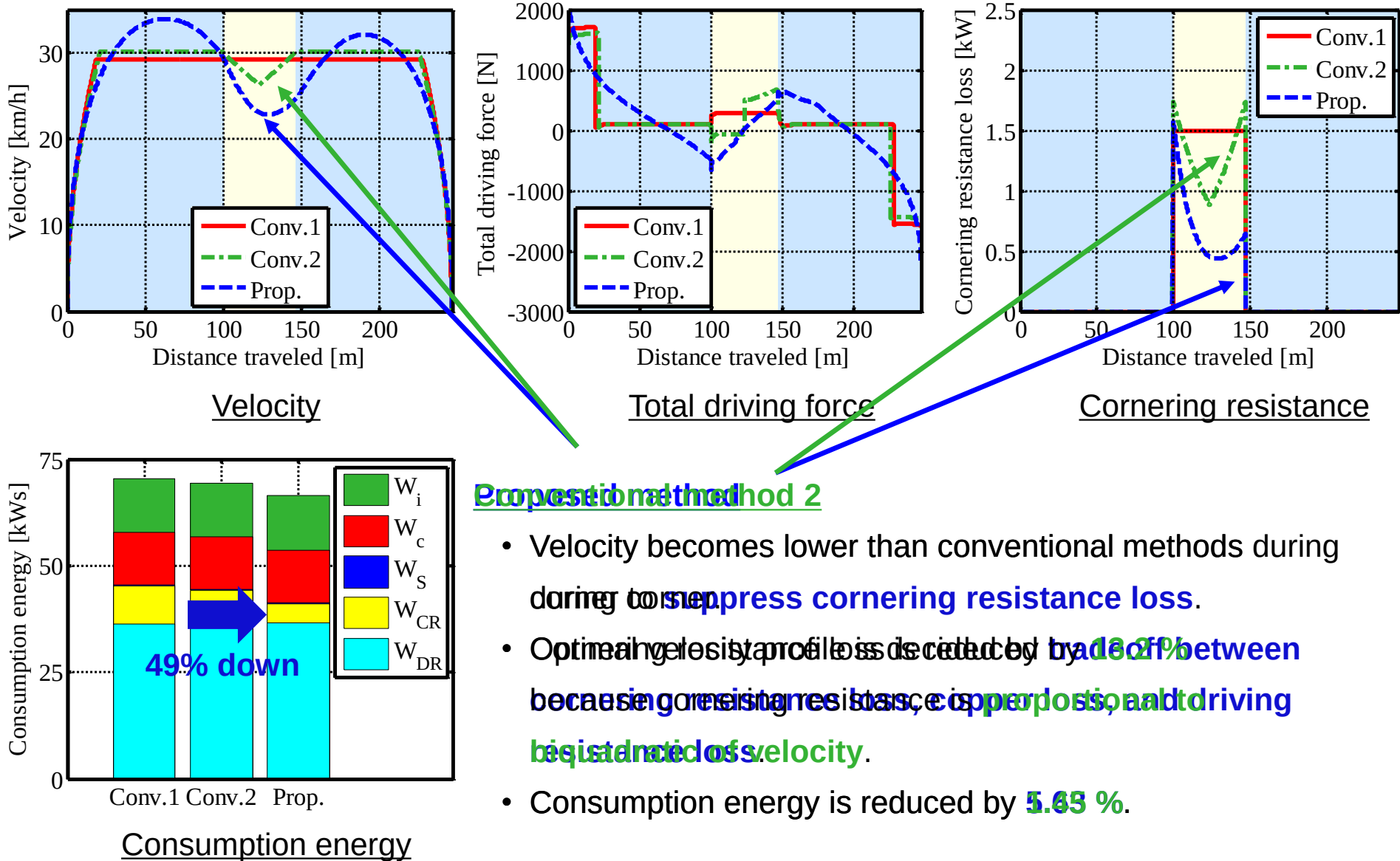
Integrated value

$$W_X = \int_{t_0}^{t_f} P_X(\mathbf{x}(t), \mathbf{u}(t)) dt$$



Neglected

4.3 Simulation Results





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■ 5.1 Experimental Conditions

Field Test

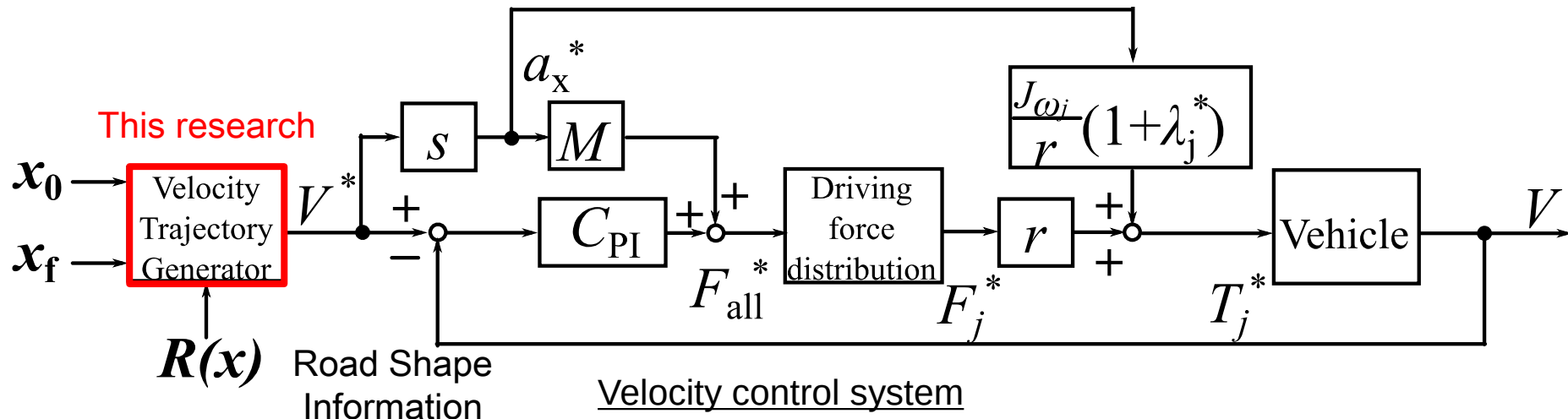
- Test course owned by National Traffic Safety and Environment Laboratory is used.

Control System

- Velocity control system is used.
- Closed-loop pole is allocated to -5 rad/s.
- Steering angle is controlled by hand to track the designated course.

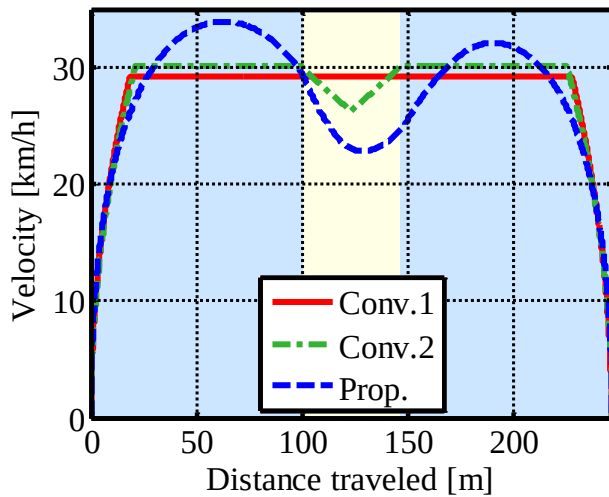


Field Test @National Traffic Safety and Environment Laboratory

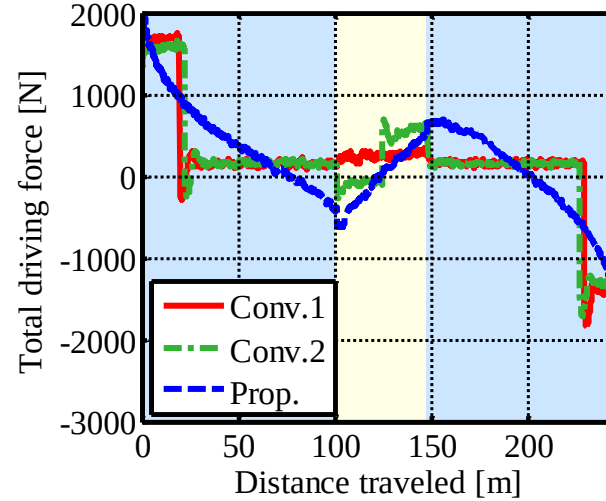


Velocity control system

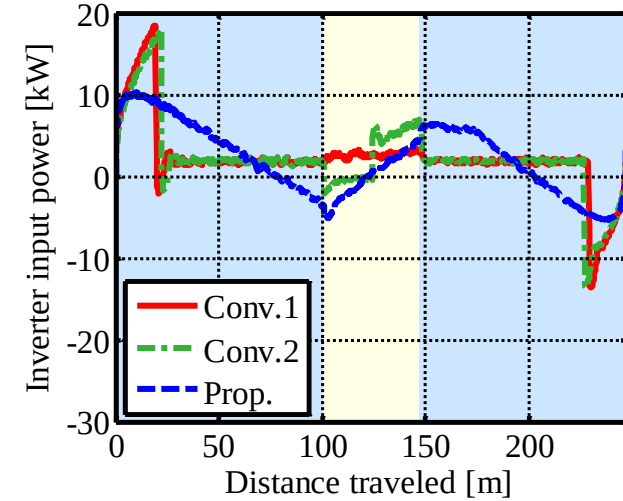
5.2 Experimental Result



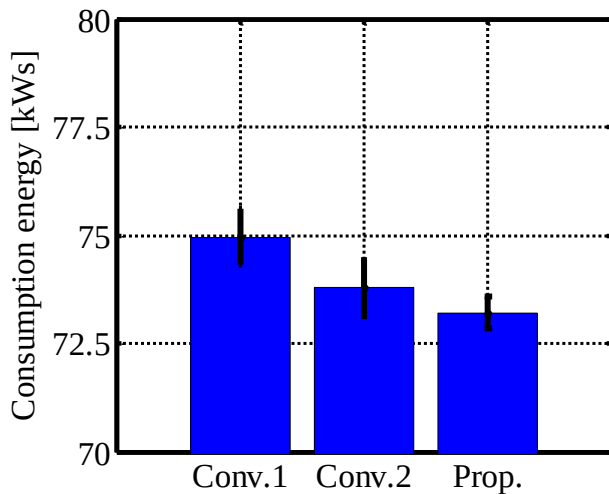
Velocity



Total driving force



Inverter input power



Consumption energy

- Total driving force shows **same tendency as simulation.**
- Modeling of driving resistance and cornering resistance is valid.
- Proposed method reduces consumption energy by **2.33 %**.





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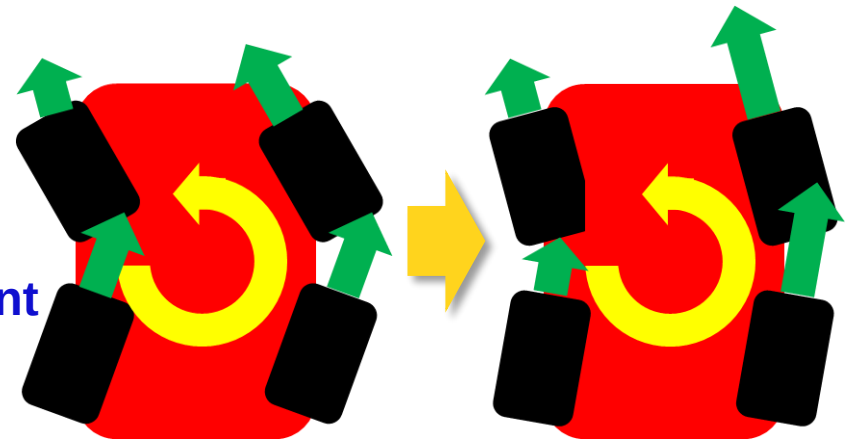
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■ 6. Conclusion

- ✓ **Range Extension Autonomous Driving (READ) system** is extended to be applied to curvy road.
- ✓ The cornering resistance is modeled on the assumption that the vehicle is brought into stationary circle turn.
- ✓ The optimal velocity profile is mainly decided by **tradeoff between copper loss, driving resistance loss, and cornering resistance loss**.
- ✓ **The effectiveness of the proposed method is verified** by simulations and experiments.

Future Work

- ✓ **Velocity profile** and **direct yaw moment** are optimized simultaneously to reduce consumption energy.

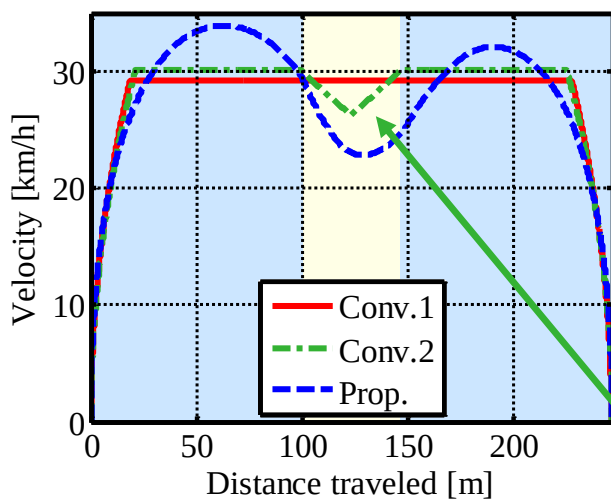


Direct yaw moment

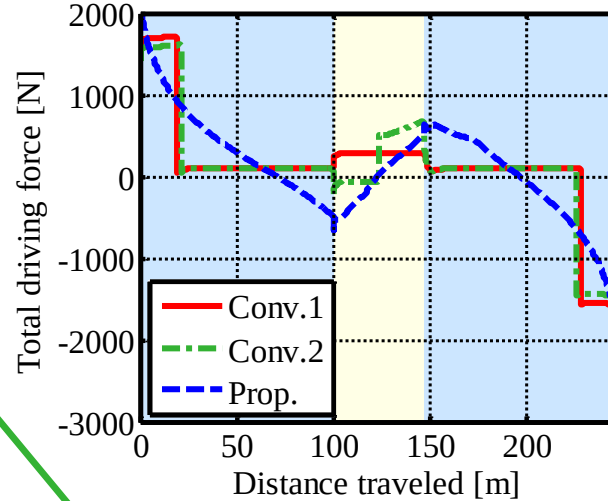


■ Appendix

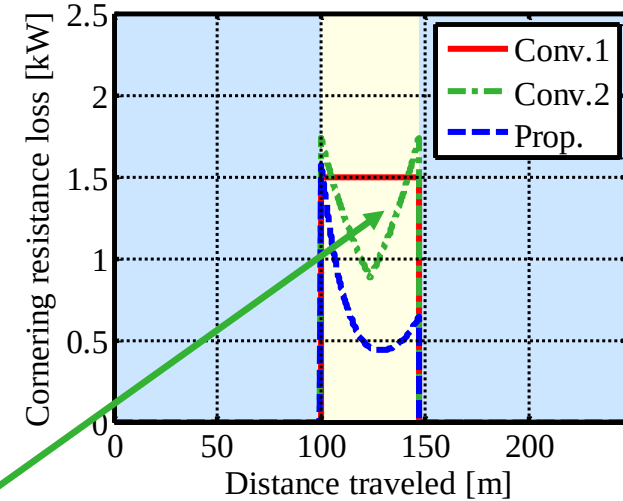
4.3 Simulation Results



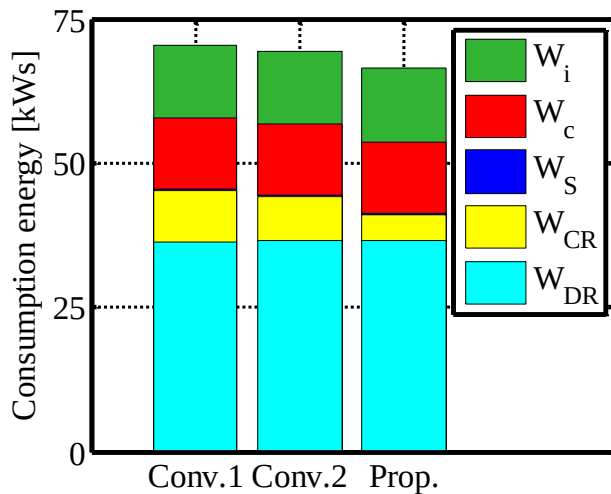
Velocity



Total driving force



Cornering resistance

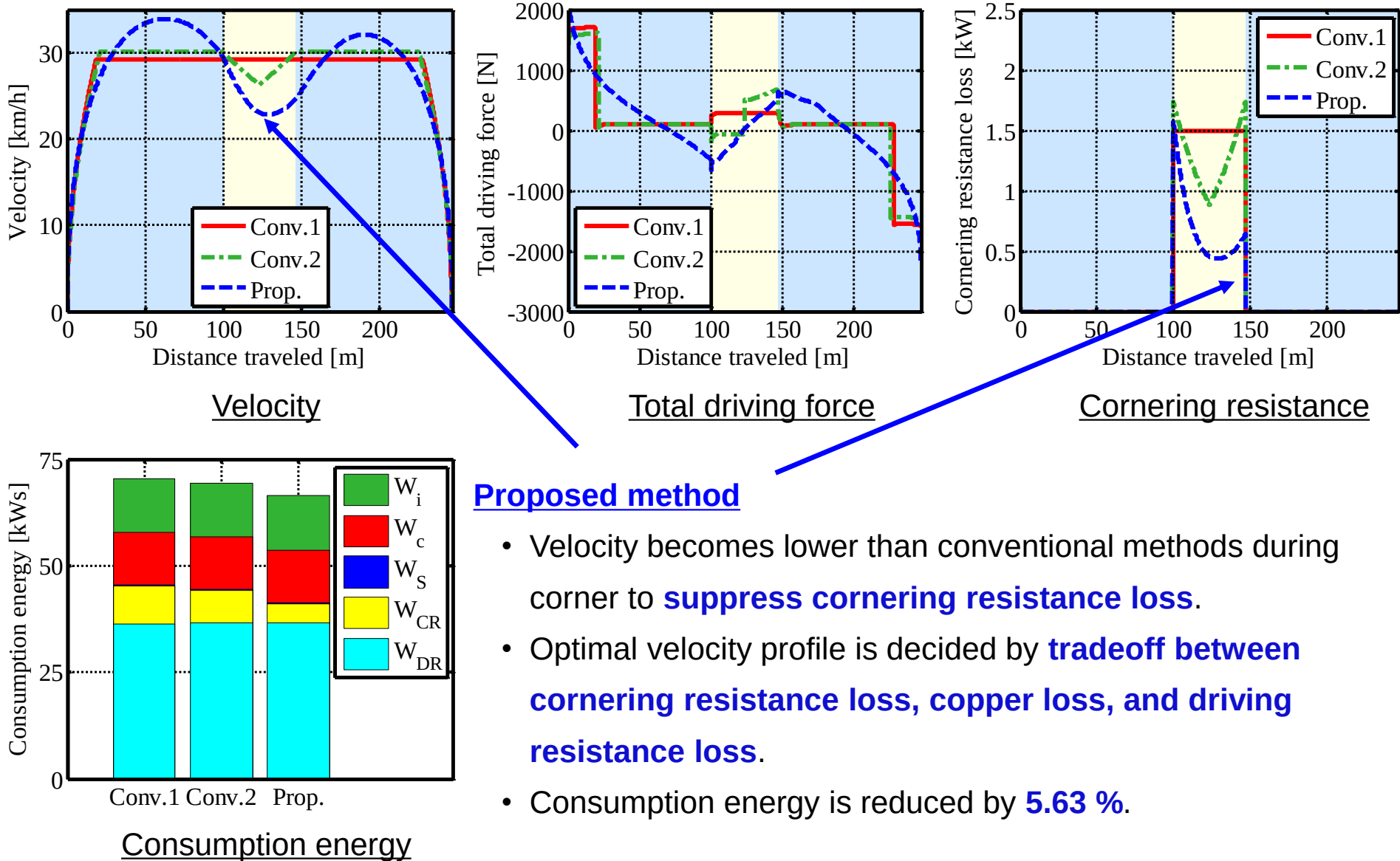


Consumption energy

Conventional method 2

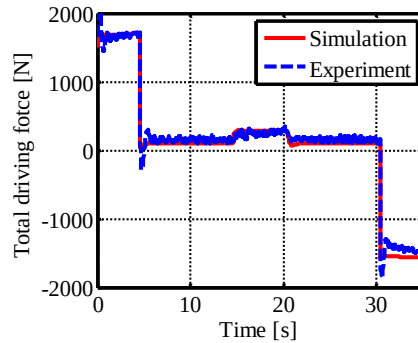
- Velocity becomes lower than conventional methods during corner.
- Cornering resistance loss is reduced by **13.2 %** because cornering resistance is **proportional to biquadratic of velocity**.
- Consumption energy is reduced by **1.45 %**.

4.3 Simulation Results

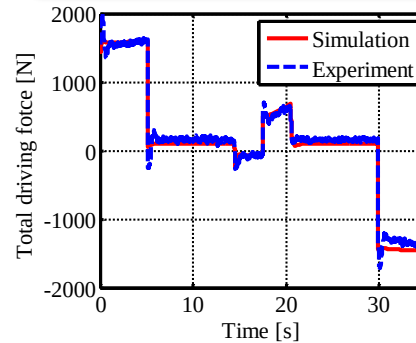


■ Simulation Results & Experimental Results

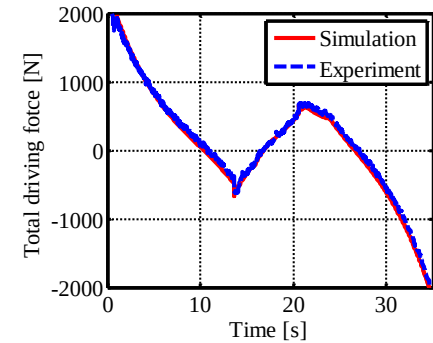
Total driving force



Conventional 1

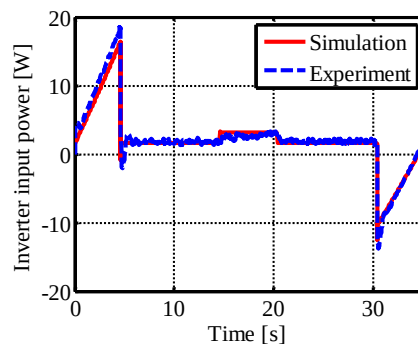


Conventional 2

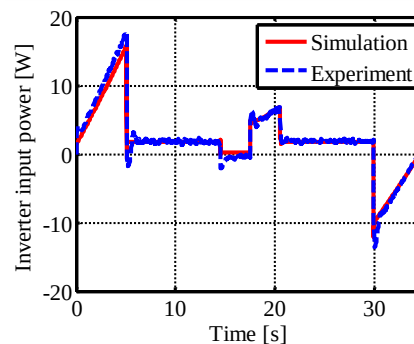


Proposed

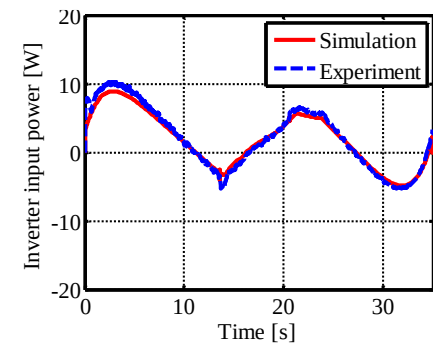
Inverter input power



Conventional 1



Conventional 2

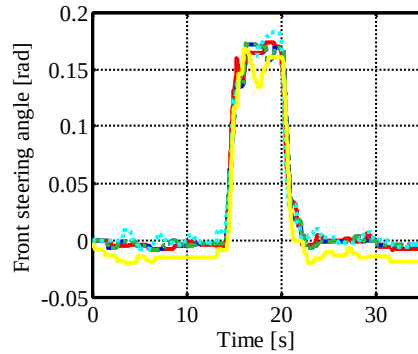


Proposed

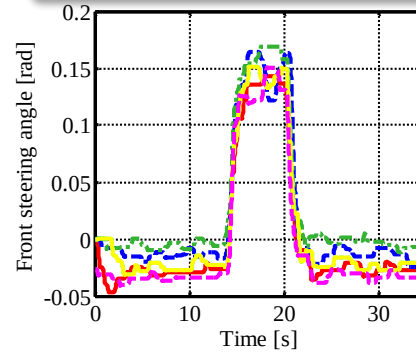
Total driving force and inverter input power show same tendency as simulation

■ Experimental Results

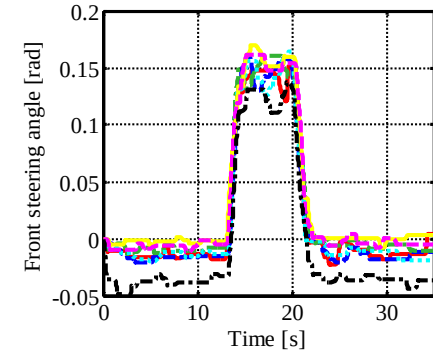
Front steering angle



Conventional 1

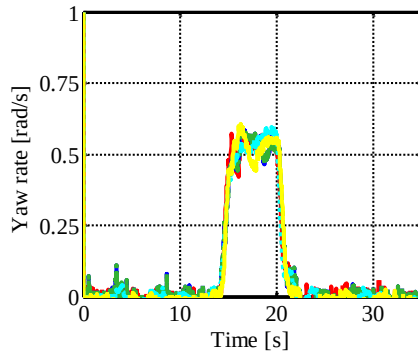


Conventional 2

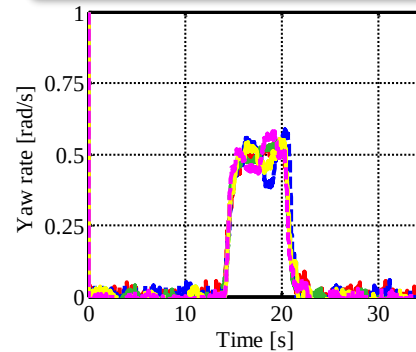


Proposed

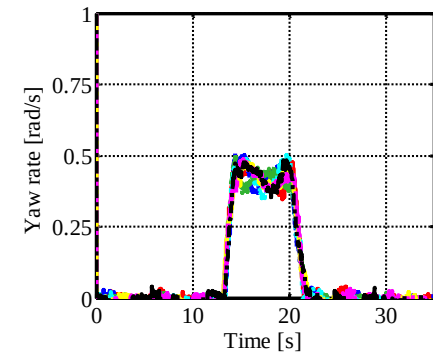
Yaw rate



Conventional 1

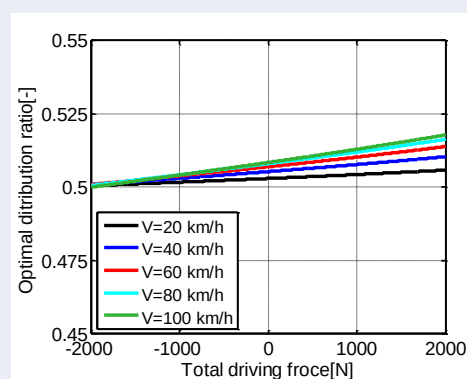
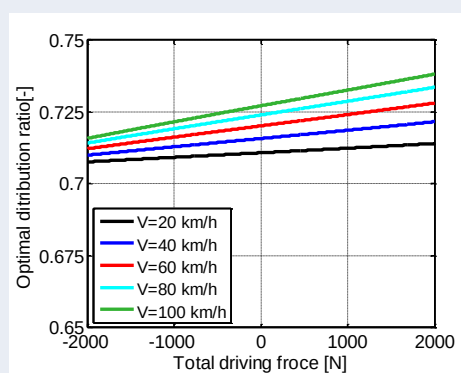
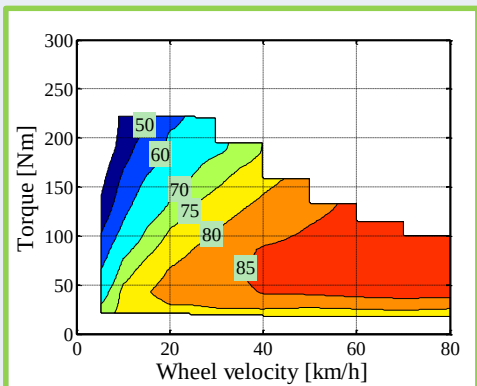
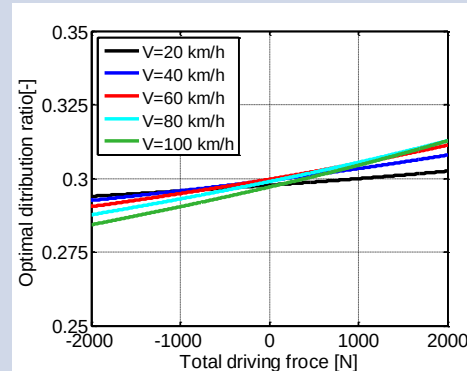
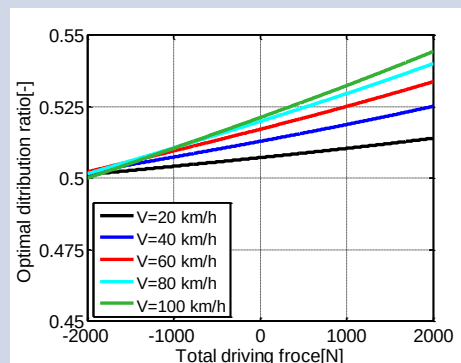
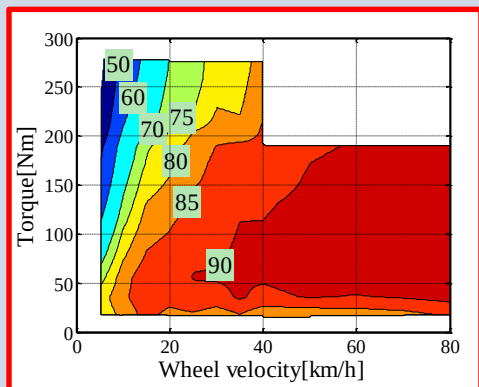
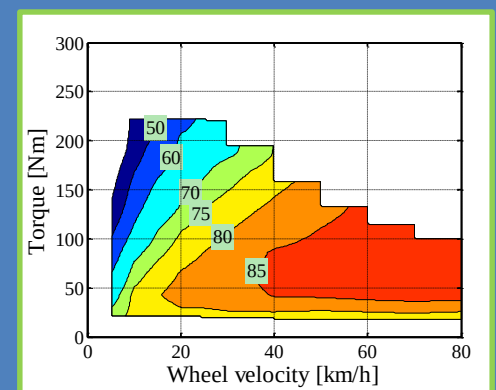
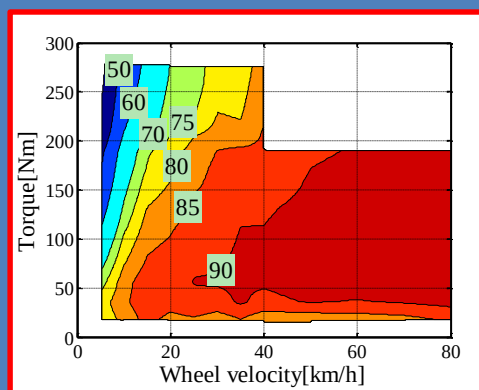
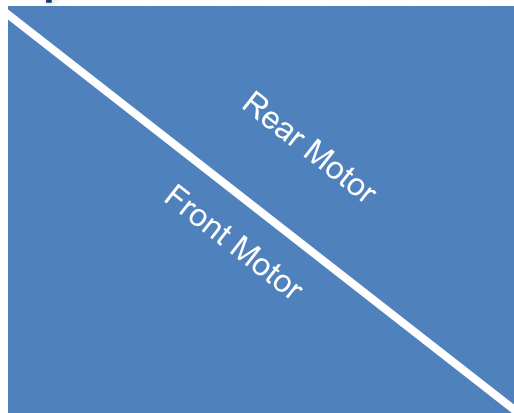


Conventional 2



Proposed

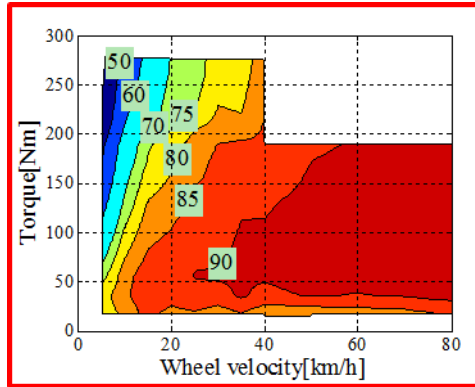
Optimal Distribution Ratio (1)



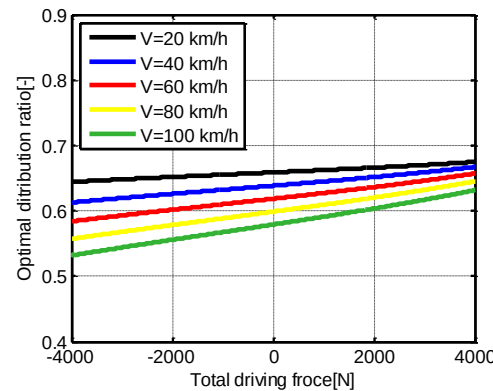
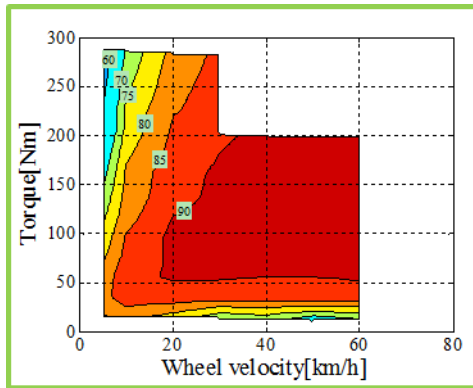
■ Optimal Distribution Ratio (2)

Minimize $P_{in}(t)$ by optimizing $k(t)$

Front

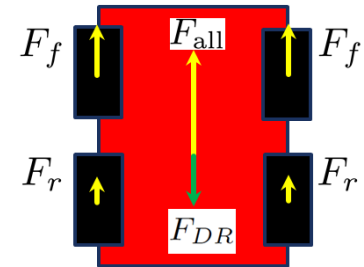


Rear



Optimal distribution ratio

Driving-braking force distribution



$$F_j(k) = \frac{1}{2} \gamma_j(k) F_{all}$$

$$\gamma_j(k) = \begin{cases} 1 - k & (j = f) \\ k & (j = r) \end{cases}$$

$$k_{opt}(V, F_{all}) = \frac{\frac{V}{D_s' N_f(V, F_{all})} + \frac{r^2 R_f}{K_{tf}^2} + \frac{V^2}{R_{cf}(V)} \left(\frac{L_{qf}}{\Psi_f} \right)^2}{\frac{V}{D_s'} \sum_{j=f,r} \frac{1}{N_j(V, F_{all})} + r^2 \sum_{j=f,r} \frac{R_j}{K_{tj}^2} + V^2 \sum_{j=f,r} \frac{1}{R_{cj}(V)} \left(\frac{L_{qj}}{\Psi_j} \right)^2}$$

Mechanical output
Copper loss
Iron loss

■ Euler-Lagrange Equation

Penalty function

$$P(\mathbf{x}(t_f)) = \frac{1}{2}\sigma \|\psi(\mathbf{x}(t_f))\|^2$$

Hamiltonian function

$$H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu}) = P_{\text{in}}(\mathbf{x}, \mathbf{u}) + \boldsymbol{\nu}(t)^T \mathbf{f}(V, F_{\text{all}})$$

Objective function

$$J = P(\mathbf{x}(t_f)) + \int_{t_0}^{t_f} \{ H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu}) - \boldsymbol{\nu}(t)^T \dot{\mathbf{x}} \} dt$$

Euler-Lagrange Equation

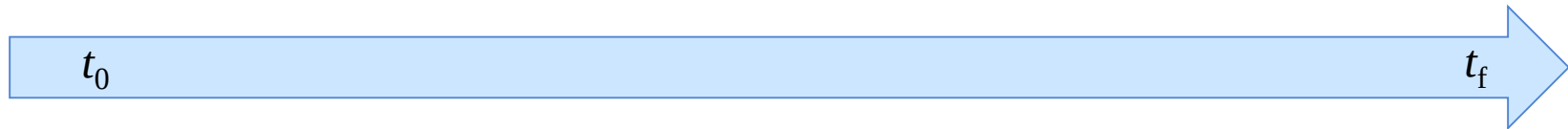
$$\begin{aligned} \dot{\boldsymbol{\nu}} &= - \left(\frac{\partial H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu})}{\partial \mathbf{x}} \right)^T & \boldsymbol{\nu}(t_f) &= \left(\frac{\partial P(\mathbf{x})}{\partial \mathbf{x}} \right)^T \Big|_{t=t_f} \\ \frac{\partial H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu})}{\partial \mathbf{u}} &= \mathbf{0} & \left(\frac{\partial P(\mathbf{x})}{\partial t} + H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu}) \right) \Big|_{t=t_f} &= 0 \end{aligned}$$

■ Steepest Descent Method

1. Appropriate initial solution $\mathbf{u}(t)$ ($t_0 \leq t \leq t_f$) is supplied

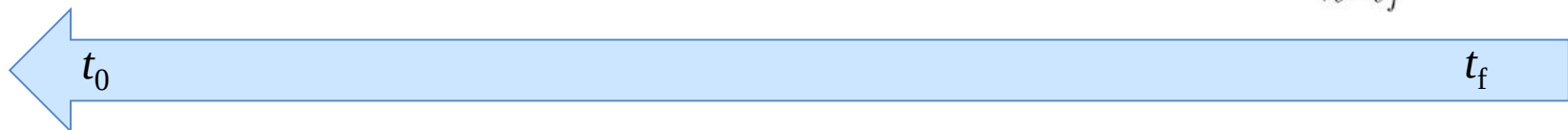
2. State variable $\mathbf{x}(t)$ ($t_0 \leq t \leq t_f$) is calculated

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) \quad \mathbf{x}(t_0)$$



3. Adjoint variable $\boldsymbol{\nu}(t)$ ($t_0 \leq t \leq t_f$) is calculated

$$\dot{\boldsymbol{\nu}} = - \left(\frac{\partial H(\mathbf{x}, \mathbf{u}, \boldsymbol{\nu})}{\partial \mathbf{x}} \right)^T \quad \boldsymbol{\nu}(t_f) = \left(\frac{\partial P(\mathbf{x})}{\partial \mathbf{x}} \right)^T \Big|_{t=t_f}$$



4. Control signal $\mathbf{u}(t)$ ($t_0 \leq t \leq t_f$) is updated to minimize objective function

$$\mathbf{u}_{update}(t) = \mathbf{u}(t) + \alpha \mathbf{s}(t) \quad \mathbf{s} = - \left(\frac{\partial H}{\partial \mathbf{u}} \right)^T$$