Introducing hybrid vehicle dynamics in microscopic traffic simulation

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Publication date:
2023-01-09

Permanent link:
https://doi.org/10.3929/ethz-b-000594749

102nd Annual Meeting ▲ January 8–12, 2023 ▲ Washington, DC

TRB ANNUAL MEETING

Introducing Hybrid Vehicle Dynamics in Microscopic Traffic Simulation

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- Generic hybrid MFC model
- Experimental setup
- Results and discussion
- Conclusions

Background & motivation

➢ Challenges and opportunities for road transport

Oil dependency

95% of motor vehicles depend on oil for energy

Emissions

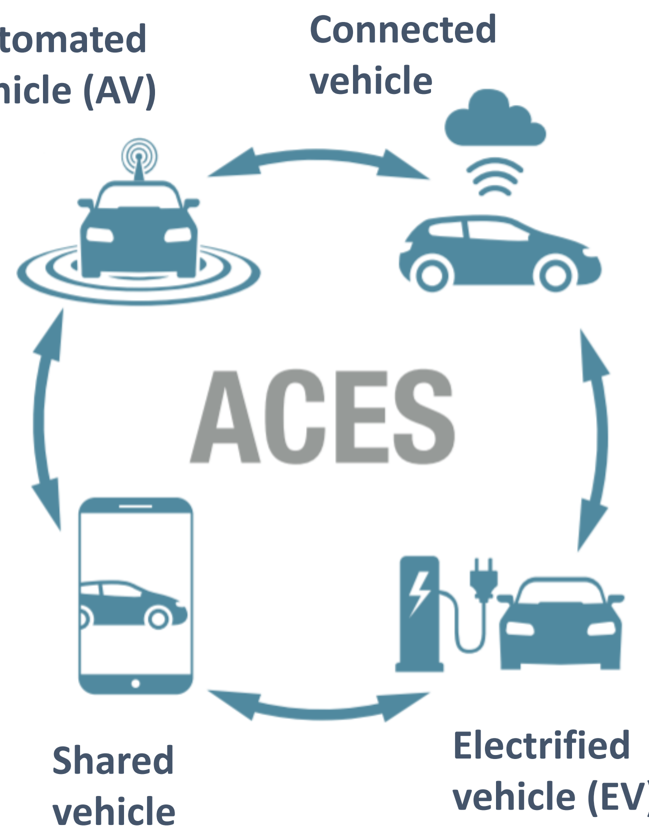
20% of GHG emissions come from combustion engines

Safety

1.2 million people die on the road each year

Congestion

$305 billion are lost each year in the US due to jams



Traffic simulation → Technology development and evaluation

Background & motivation

➢ Our previous studies

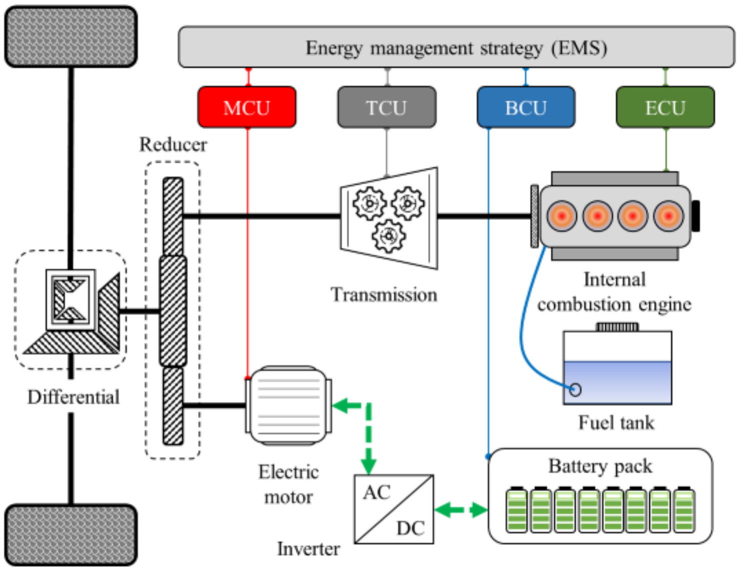
Microsimulation free-flow acceleration (MFC) models → Dynamics of **ICEVs** and **EVs**, which are directly **propelled by a single type** of power source (ICE or EM).

He et al. Transp. Res. Rec. 2020;2674(9):776-91; Makridis et al. Transp. Res. Rec. 2019;2673(4):762-77.

➢ Research gap

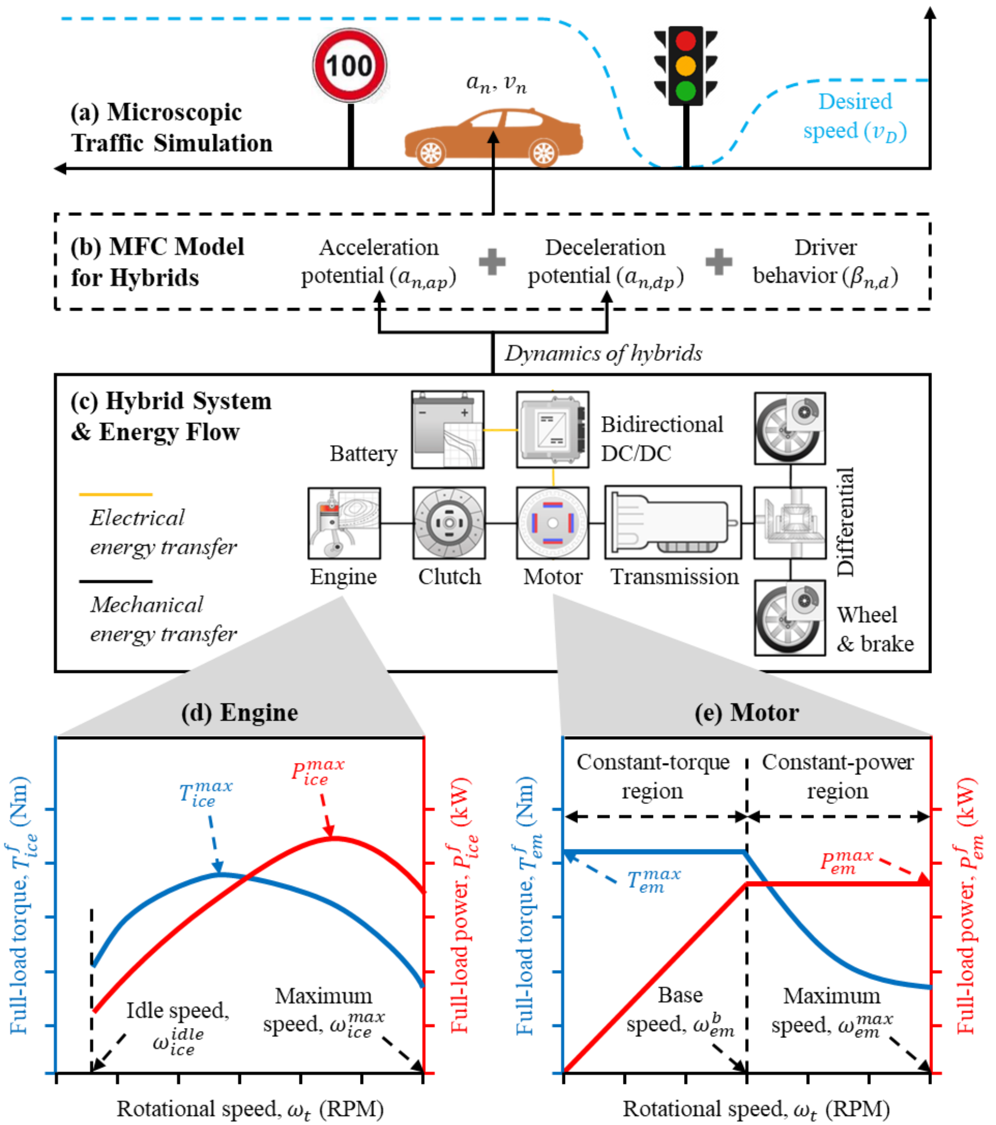
No traffic model accounts for vehicle dynamics of **HEVs** (propelled by EM alone or together with ICE, depending on battery SoC and power demand).

Challenge: HEVs have more degrees of freedom for propulsion → More complex acceleration characteristics.



Generic hybrid MFC model

- **Overview**
  - **(d) & (e)** Power sources: ICE & EM, *different propulsion characteristics*
  - **(c)** Energy flows: Electrical & mechanical
  - **(b)** MFC model:
    - ✓ Dynamics of hybrids $a_{n,ap}$ & $a_{n,dp}$
    - ✓ Driver behavior: $\beta_{n,d}$



Generic hybrid MFC model

Model inputs Vehicle specifications and other parameters

- **Acceleration potential,** $a_{n,ap}$

  The hybrid's propulsion capability

- **Deceleration potential,** $a_{n,dp}$

  The hybrid's braking capability

- **Driver behaviour,** $\beta_{n,d}$

  The driver's or controller's willingness to use the above capabilities.

Model output Vehicle acceleration a_n

Generic hybrid MFC model

- **Acceleration potential function, $a_{n,ap}(t)$**

$$a_{n,ap}(t) = \frac{F_T^f\left(v_n(t)\right) - F_R\left(v_n(t)\right)}{m},$$

v_n is the vehicle speed (m/s); m is the vehicle operating mass (kg); F_T^f and F_R are the full load tractive force (N) and the total resistance force (N), respectively.

$$F_R(t) = f_0 \cdot \cos(\theta(t)) + f_1 \cdot v_n(t) + f_2 \cdot v_n(t)^2 + mg \cdot \sin\left(\theta(t)\right),$$

θ is the road slope (rad); f_0, f_1, and f_2 are road load coefficients (N, kg/s, and kg/m, respectively).

Generic hybrid MFC model

$$F_T^f(t) = \min\left(\frac{T_T^f(v_n(t))}{r_w}, \mu \cdot m_{ta} \cdot g\right),$$

T_T^f is the full load tractive torque (Nm); r_w is the wheel radius (m); μ is the coefficient of friction between wheels and roadway surface; m_{ta} is the mass of the vehicle on the tractive axle (kg); g is the gravitational acceleration (9.81 m/s^2).

$$T_T^f(t) = \begin{cases} T_{em}^f(\omega_t(t)) \cdot i_t \cdot i_d \cdot \eta_d, & \text{for CD mode,} \quad \text{(Charge depleting)} \\ \left(T_{em}^f(\omega_t(t)) + T_{ice}^f(\omega_t(t))\right) \cdot i_t \cdot i_d \cdot \eta_d, & \text{for CS mode,} \quad \text{(Charge sustaining)} \end{cases}$$

T_{em}^f and T_{ice}^f are full load torques of the electric motor (EM) and the internal combustion engine (ICE), respectively; ω_t is the rotational speed (rpm) of the transmission input shaft; i_t and i_d are the engaged gear ratios of the transmission and the differential, respectively; η_d is the driveline efficiency.

Generic hybrid MFC model

$$\omega_t(t) = \frac{60 \cdot i_t \cdot i_d \cdot v_n(t)}{2\pi \cdot r_w},$$

This equation represents the conversion between ω_t and v_n. Relevant parameters and variables are given previously.

$$T_{em}^{f}(t) = \begin{cases} T_{em}^{max}, & 0 \le \omega_t\,(t) < \omega_{em}^{b}, \\ \dfrac{6 \times 10^4 \cdot P_{em}^{max}}{2\pi \cdot \omega_t(t)}, & \omega_{em}^{b} \le \omega_t(t) < \omega_{em}^{max}, \end{cases} \qquad \omega_{em}^{b}(t) = \frac{6 \times 10^4 \cdot P_{em}^{max}}{2\pi \cdot T_{em}^{max}},$$

T_{em}^{max} and P_{em}^{max} are the EM's maximum torque (Nm) and maximum power (kW), respectively; ω_{em}^{b} is the motor base speed (rpm) representing the split point between constant-torque and constant-power regions.

$$T_{ice}^{f}(t) = \frac{6 \times 10^4 \cdot P_{ice}^{f}\big(\omega_t(t)\big)}{2\pi \cdot \omega_t(t)},$$

P_{ice}^{f} are the ICE's full load power (kW) derived from the CO2MPAS generic ICE model.

Generic hybrid MFC model

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- **Deceleration potential function,** $a_{n,dp}(t)$

$$a_{n,dp}(t) = \varepsilon\big(v_n(t)\big) \cdot a_d^{lim},$$

$$a_d^{lim} = \mu \cdot g,$$

$$\varepsilon(t) = b_0 + b_1 \cdot v_n(t) + b_2 \cdot v_n(t)^2,$$

a_d^{lim} is the maximum frictional deceleration (m/s^2) that can be sustained between the tires and the roadway surface; ε is a reduction factor representing the driver’s typical deceleration pattern at different speeds, in which b_0, b_1, and b_2 are empirical coefficients.

Generic hybrid MFC model

➢ **Driver behaviour function, $\beta_{n,d}(t)$**

$$\beta_{n,d}(t) = \max\left[1 - \left(1 + \frac{2(v_n(t) - v_D)}{v_D + 0.1}\right)^{30}, 1 - \left(1 - \frac{v_n(t) - v_D}{50}\right)^{100}\right],$$

$$a_n(t) = \begin{cases} DS \cdot \beta_{n,d}\big(v_n(t)\big) \cdot a_{n,ap}\big(v_n(t)\big), & 0 \leq v_n(t) < v_D, \\ DS \cdot \beta_{n,d}\big(v_n(t)\big) \cdot a_{n,dp}\big(v_n(t)\big), & v_n(t) \geq v_D, \end{cases}$$

v_D is the desired speed (m/s) in free-flow traffic; $\beta_{n,d}$ denotes the percentage of the acceleration and deceleration capabilities that drivers typically use under different conditions.

- Driver style factor: $DS \in [0,1]$ → the aggressiveness in acceleration and deceleration.
- Gear-shifting factor: $GS \in [0,1]$ → the threshold speeds for gear shifting based on the habits of drivers.

Makridis et al. Transp. Res. Rec. 2019;2673(4):762-77.

Experimental setup

The experimental setup has 4 stages:

- Validation with VELA chassis dynamometer data to validate the reliability of the acceleration ($a_{n,ap}$) and deceleration ($a_{n,dp}$) potential functions
- Implementation in microsimulation
- Calibration and validation against trajectory data
- Validation with 0-100 km/h acceleration specifications for 203 commercial hybrid vehicles.

Results and discussion

➢ **Validation using chassis dynamometer test**

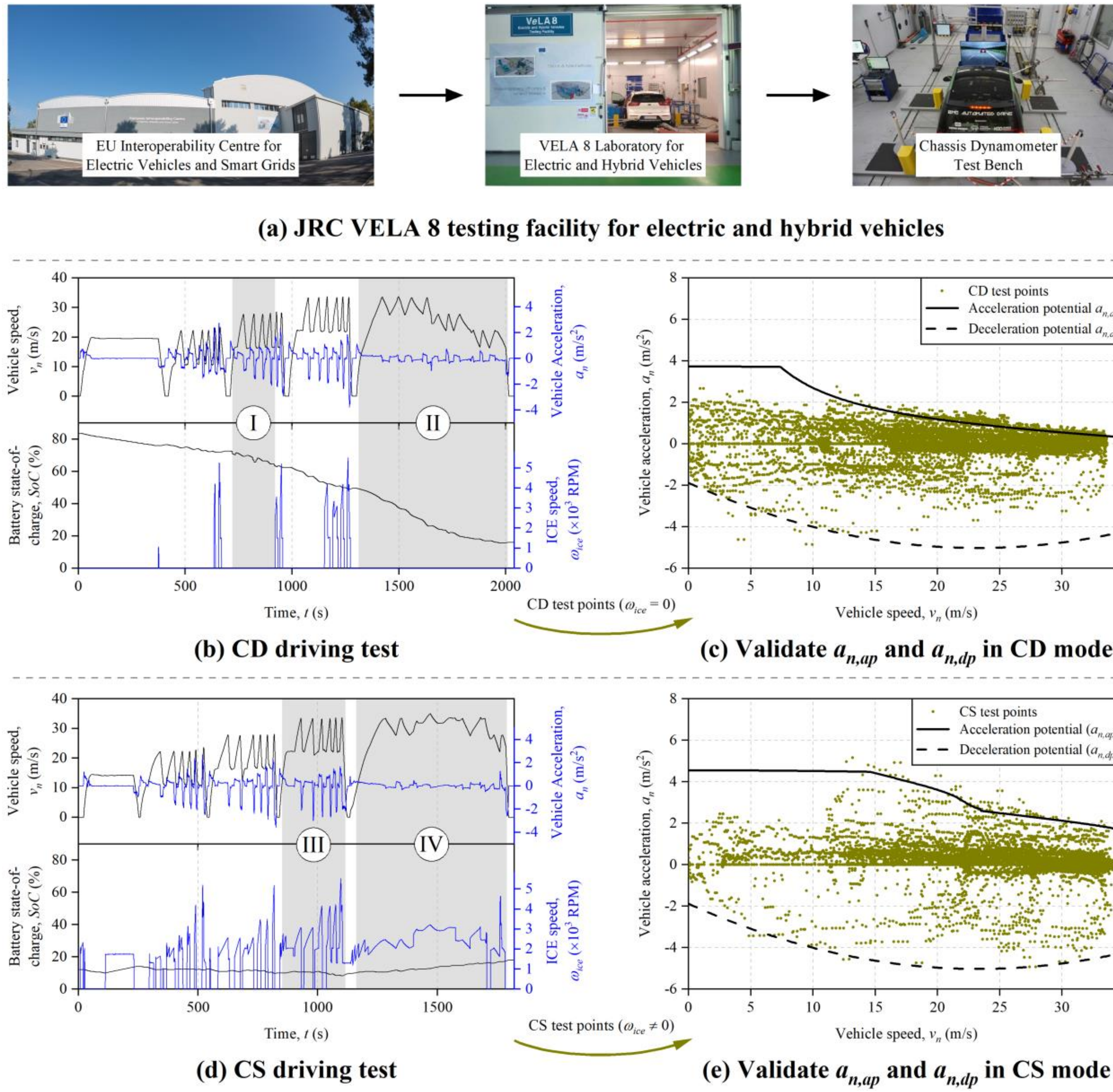
Main specifications of the hybrid vehicle under test (Kia Niro PHEV 2019)

Specifications	Symbols	Units	Values
Vehicle operating mass	m	kg	1421
Height	H	m	1.55
Width	W	m	1.81
Wheel radius	r_w	m	0.33
Transmission gear ratios	i_t	na	[3.87, 2.22, 1.37, 0.96, 0.93, 0.77], (1st to 6th)
Differential gear ratio	i_d	na	3.23
0-100 km/h acceleration time	$T_{0-100km/h}$	s	11.5
Vehicle speed limit	v_{lim}	km/h	162
Battery capacity	C_{bat}	kWh	1.56
EM's peak torque	T_{em}^{max}	Nm	44.5
EM's peak power	P_{em}^{max}	kW	170
ICE's peak torque	T_{ice}^{max}	Nm	147
ICE's peak power	P_{ice}^{max}	kW	77

Note: na = not applicable.

Results and discussion

- Two hybrid modes: (b)-(c) CD and (d)-(e) CS
- (b) and (d): Operational data in CD and CS modes
- (c) and (e): Theoretical $a_{n,ap}$ and $a_{n,dp}$ have **good correlations** with the upper and lower boundaries of the experimental data
- Trajectories I-IV → Calibrate and validate the MFC model subsequently

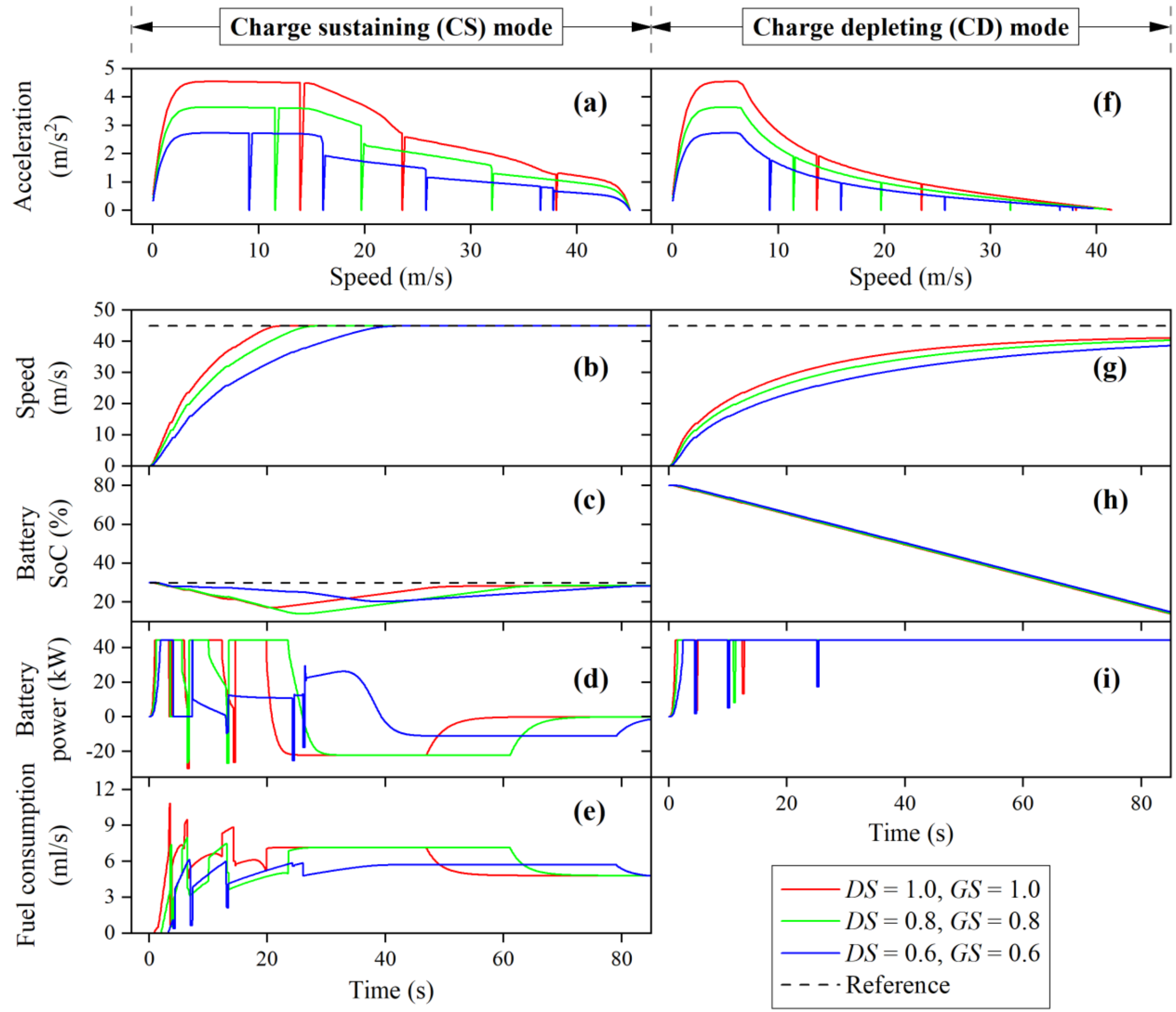


Results and discussion

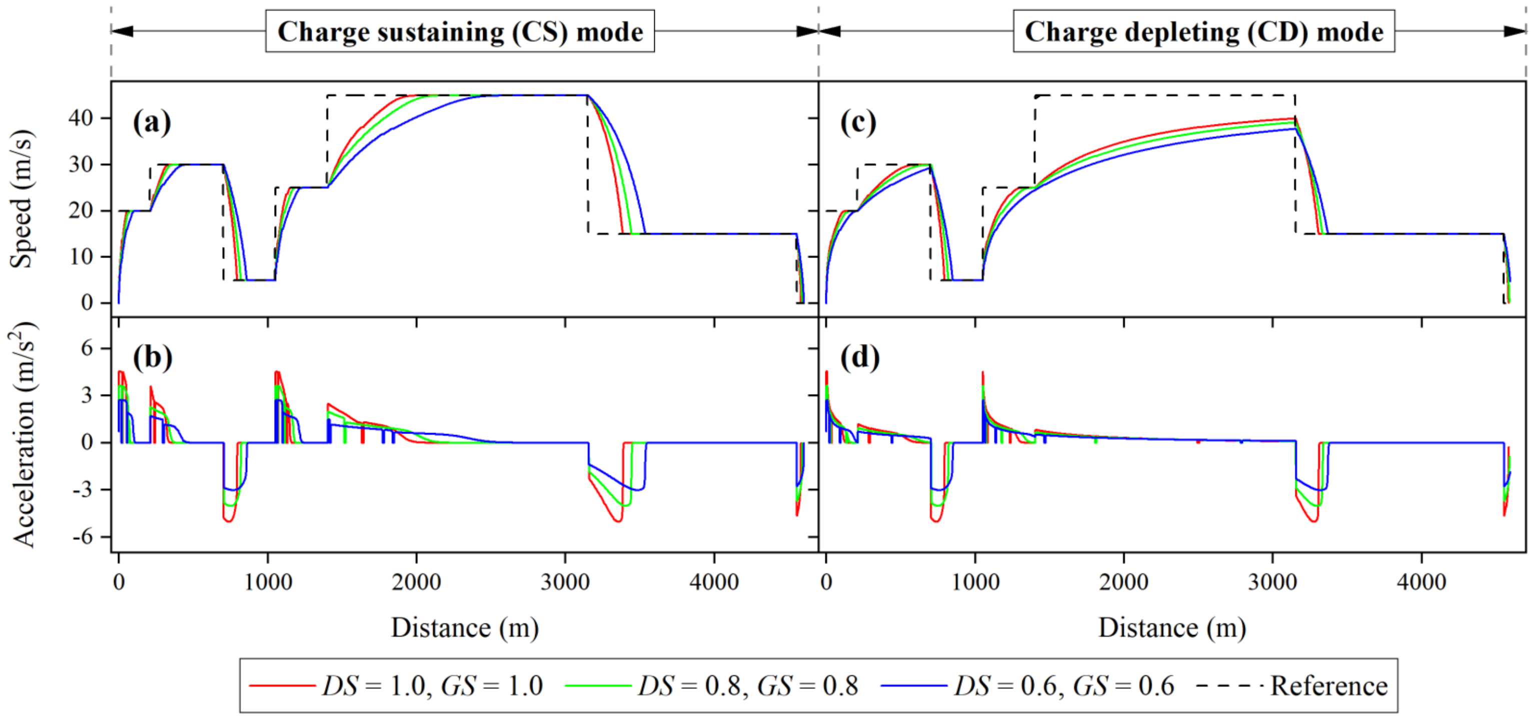
➢ Model implementation in microsimulation

a) Acceleration simulation (from 0 to 45 m/s)

- 3 typical drivers: *DS* and *GS*
- 2 modes: CS (a)-(e) and CD (f)-(i)
- (a) & (f): Smaller *GS* → Earlier gear shifting
- (b) & (g): CD mode use EM alone → Cannot reach the specified top speed (45 m/s)
- (e): aggressive driver (*DS*, *GS*) = (1, 1) → More fuel consumption



Results and discussion



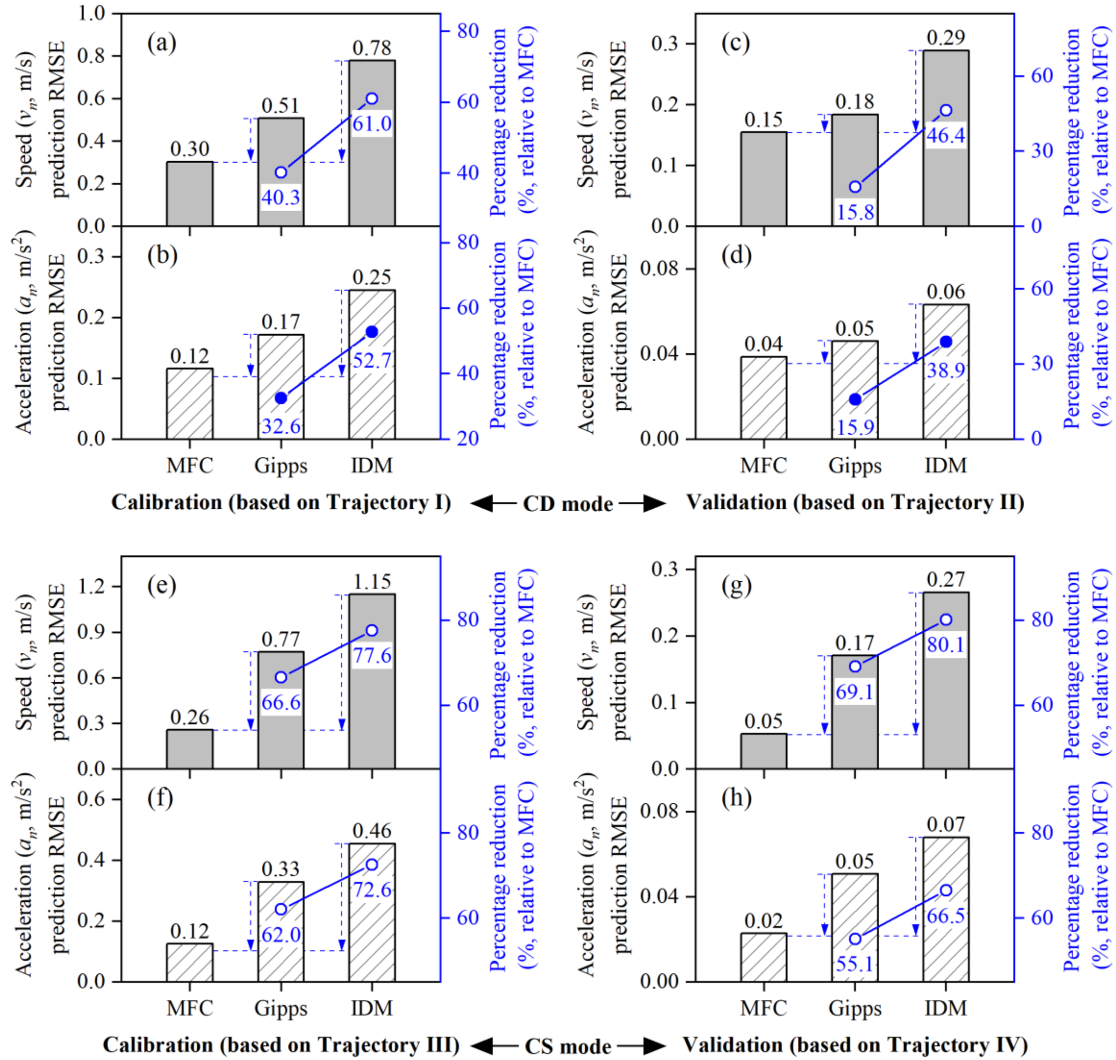
b) Artificial driving cycle simulation

- Two modes: CS (a)-(b) and CD (c)-(d)
- MFC model → Ensure smooth transitions between different speed levels → Avoid obvious oscillations or overshoots in simulation

Results and discussion

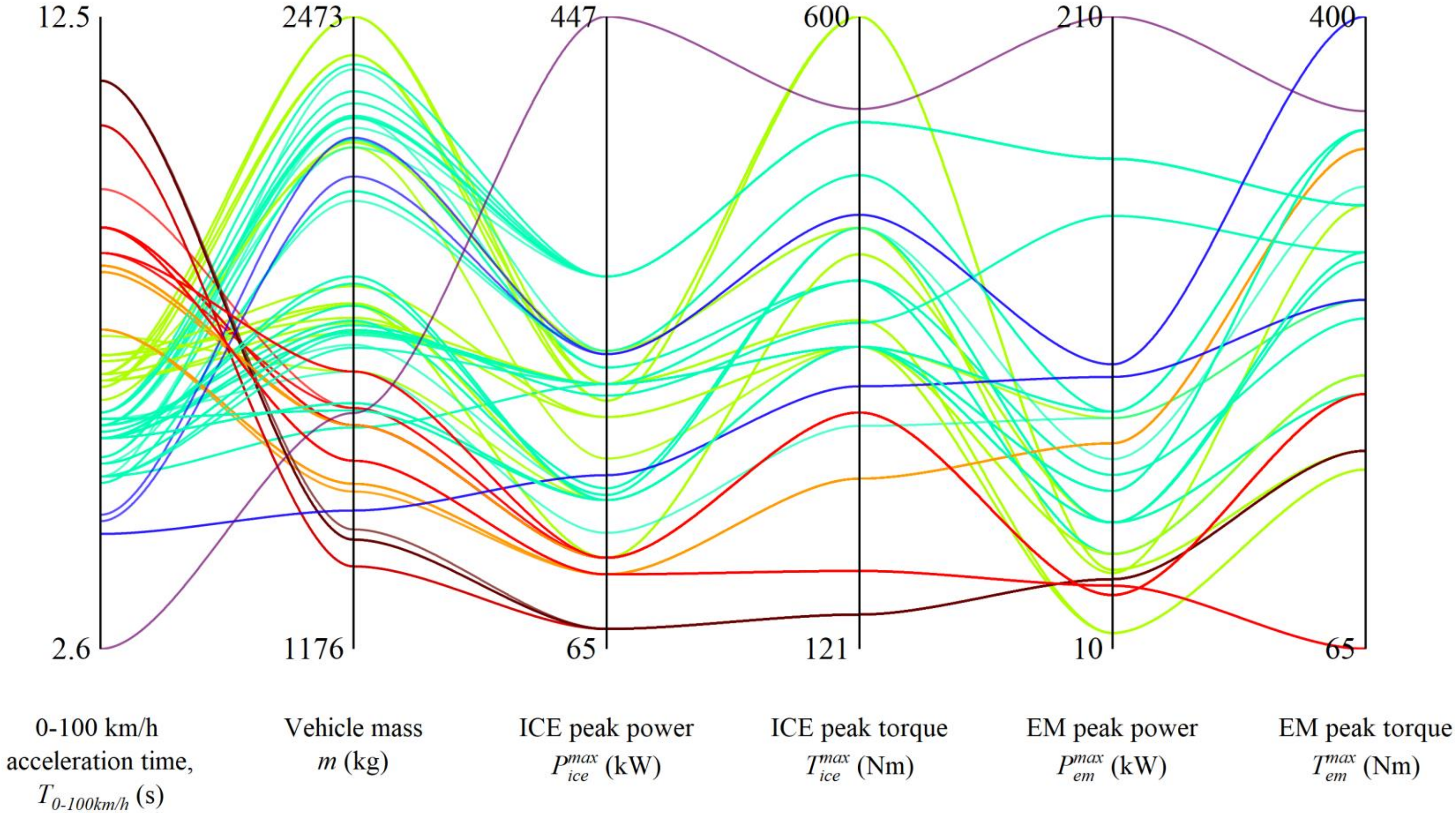
➢ Calibration and validation against driving trajectories

- 3 models: MFC, Gipps', IDM
- (a)-(b): CD calibration
- (e)-(f): CS calibration
- **Validation of CD mode →** Compared to Gipps' and IDM, MFC reduces:
  - ✓ (c) RMSE of speed
  - ✓ (d) RMSE of acceleration
- **Validation of CS mode →** MFC achieves even more accuracy gains, reducing:
  - ✓ (g) RMSE of speed
  - ✓ (h) RMSE of acceleration



Results and discussion

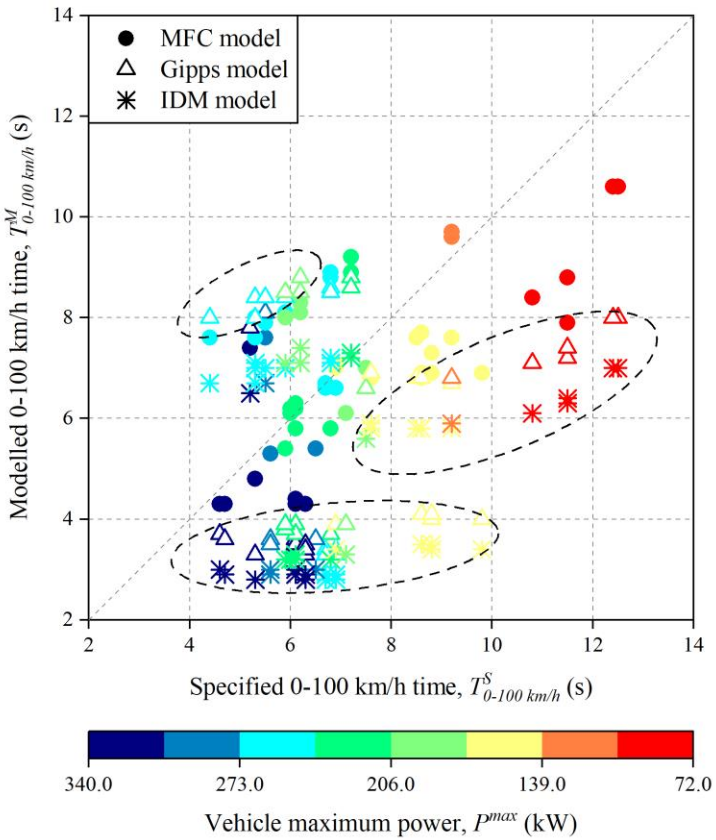
- **Validation against 0-100 km/h acceleration specifications**



Main specifications of the hybrid vehicles in the database

Results and discussion

- X axis → $T^{S}_{0-100km/h}$ (specified/ground-truth in database)
- Y axis → $T^{M}_{0-100km/h}$ (modelled/predicted by MFC, Gipps', and IDM)
- MFC cluster: Closer to the diagonal → More accurate
- Compared to Gipps' and IDM, MFC reduces RMSE of $T_{0-100km/h}$ by 40-50%.



Model	RMSE (s)	Reduction (%, relative to MFC)
MFC	1.65	na
Gipps'	3.05	45.8
IDM	3.44	51.9

Note: RMSE = root mean square error; IDM = intelligent driver model; MFC = microsimulation free-flow acceleration model; na = not applicable.

Conclusions

- MFC model is hitherto **the first traffic model** to capture the acceleration dynamics of **hybrid** vehicles.
- MFC can ensure **smooth transitions** between different speed levels, avoiding oscillations or overshoots in microsimulation.
- MFC can quantify hybrids' energy consumption (both electricity & fuel).
- MFC outperforms Gipps' and IDM in reproducing driving trajectories, **reducing validation errors** (speed & acceleration) <u>in CD mode</u>, and yielding even **greater accuracy gains** <u>in CS mode</u> (MFC captures complex ICE-EM coupling dynamics).
- MFC gives **more accurate predictions** in 0-100 km/h acceleration specifications.

Thank you!

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