

KIEVC 2026

xEV Energy Management

From Vehicle Control to Network Intelligence

Kyunghwan Choi

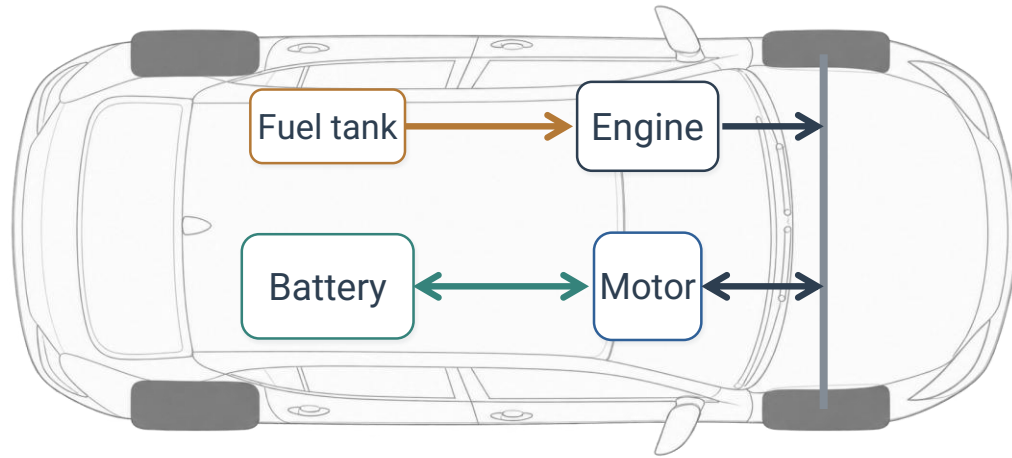
Cho Chun Shik Graduate School of Mobility, KAIST



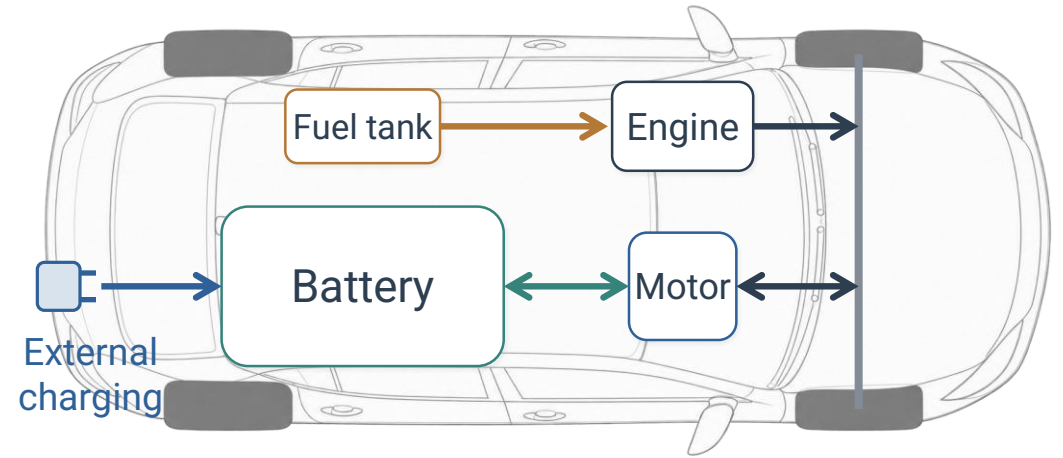
15 October 2026

xEV configurations

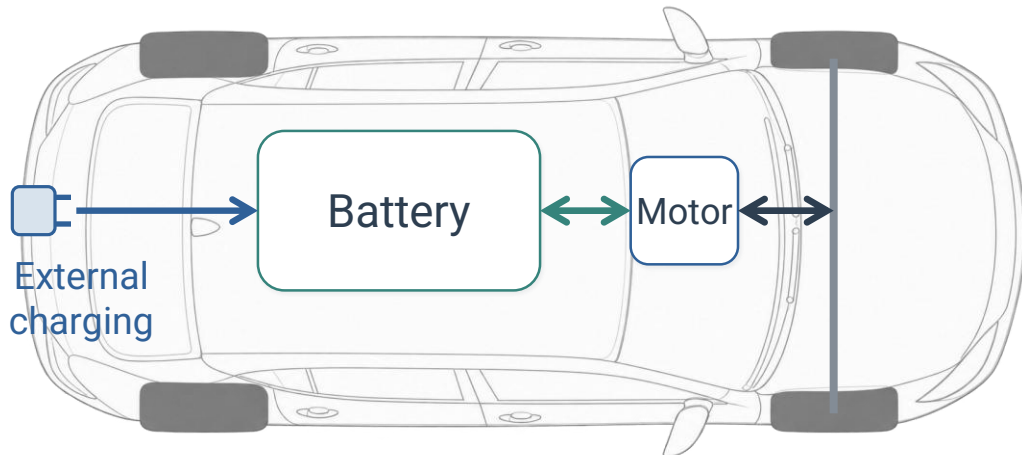
HEV · parallel hybrid



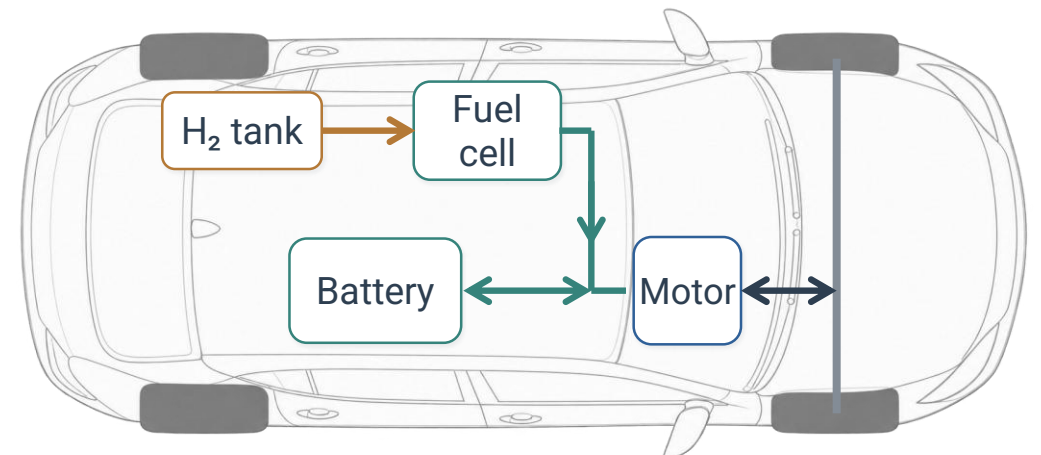
PHEV · plug-in parallel hybrid



BEV · battery electric

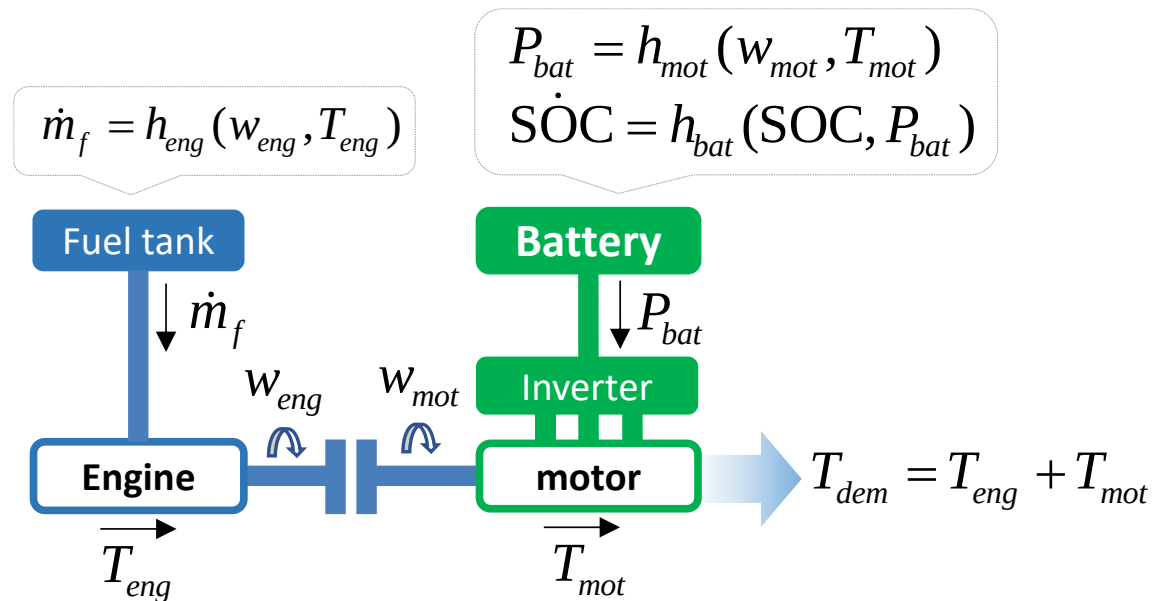


FCEV · fuel-cell electric



Energy management strategy (EMS)

Example: parallel HEV



Optimal control problem

Fuel minimization

$$\min_{T_{eng}(t)} \int_{t_0}^{t_N} \dot{m}_f(T_{eng}(t), t) dt$$

subject to

$$\dot{SOC}(t) = h_{bat}(SOC(t), T_{mot}(t), t),$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max},$$

$$SOC(t_0) = SOC_0, \quad SOC(t_N) = SOC_N,$$

$$T_{dem}(t) = T_{eng}(t) + T_{mot}(t),$$

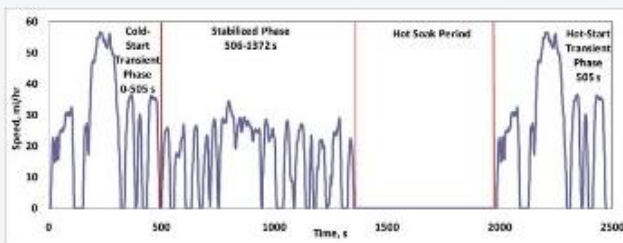
$$T_{mot,min}(t) \leq T_{mot}(t) \leq T_{mot,max}(t).$$

The EMS determines the engine-motor power split over the trip.

Rule-based EMS: a standard development workflow

Offline rule development

Target driving cycles



Optimal control problem

$$\min_{T_{\text{eng}}(t)} \int_{t_0}^{t_N} \dot{m}_f(T_{\text{eng}}(t), t) dt$$

Subject to the constraints in the EMS problem

Rule extraction (e.g., from DP)

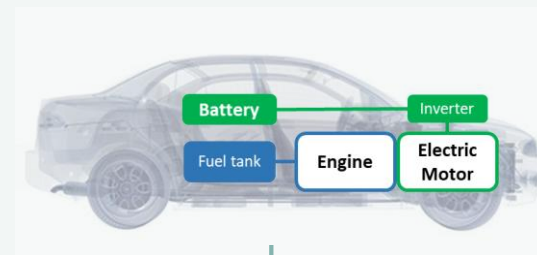
On-board control

Vehicle speed
Power demand
Battery SOC



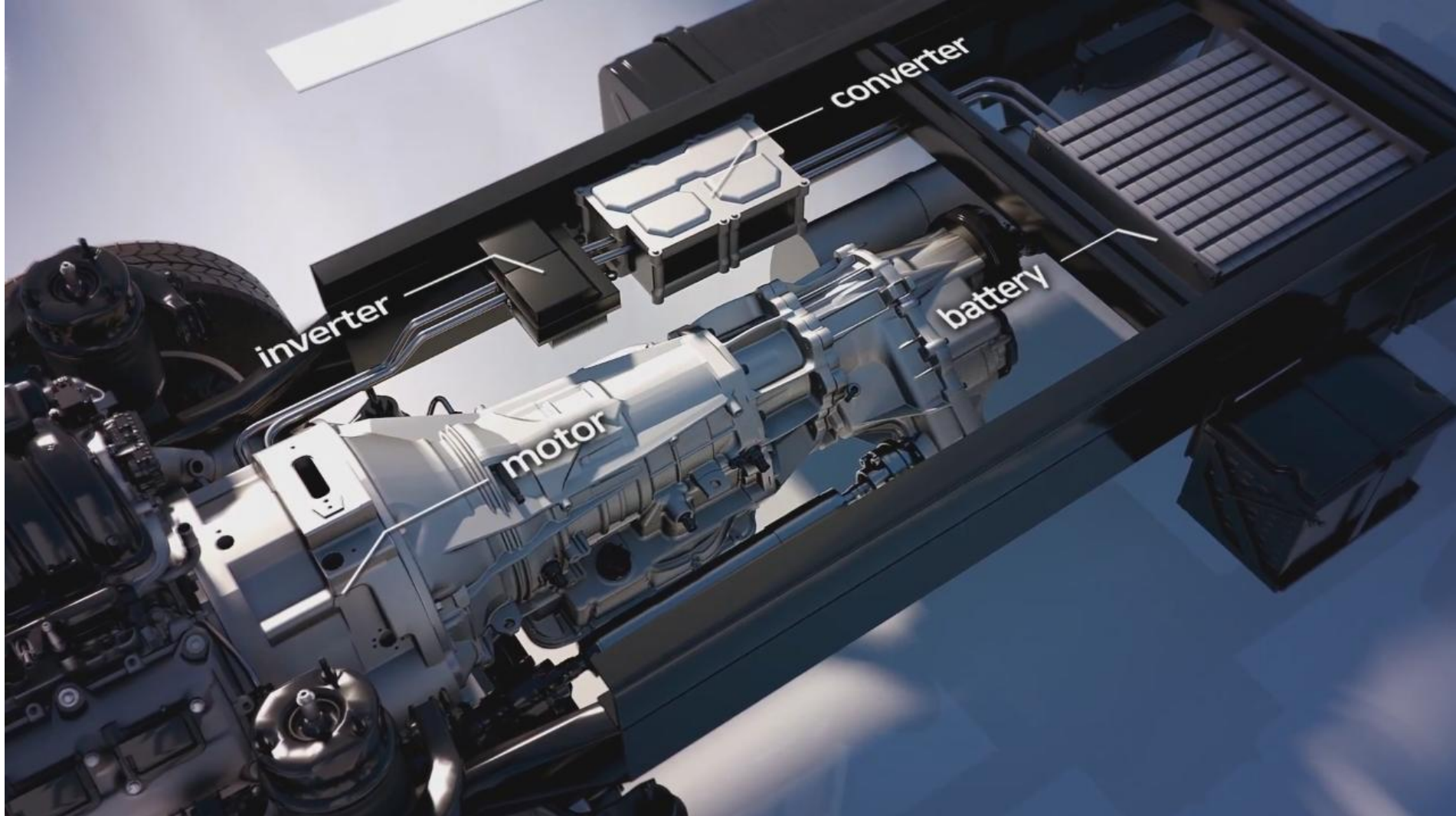
Power split

SOC feedback



Rules are tuned to the development conditions.

HEV conversion: our development case



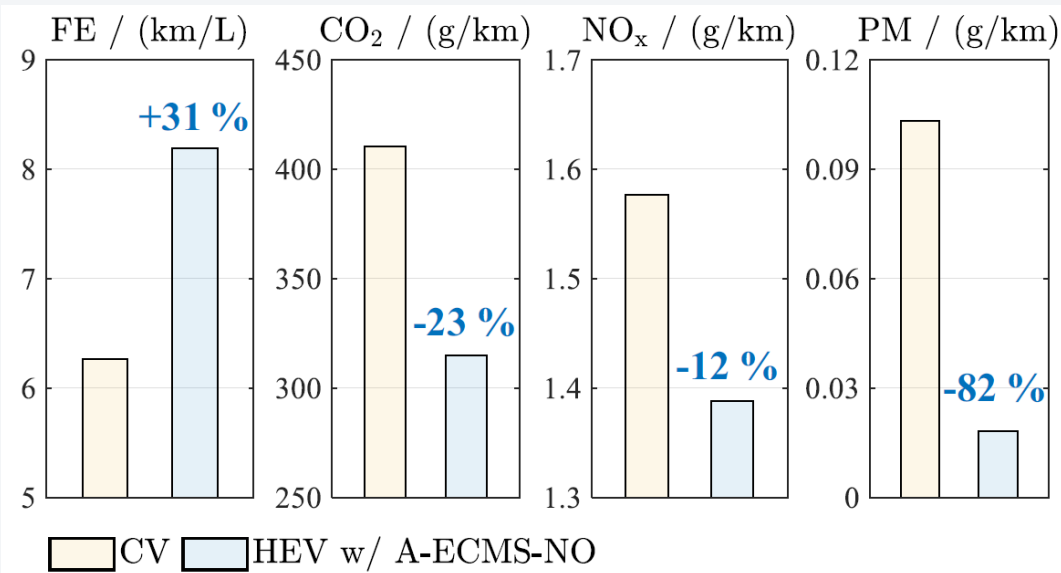
HEV conversion: test results

Converted HEV versus the original vehicle under each test condition

Certified performance test



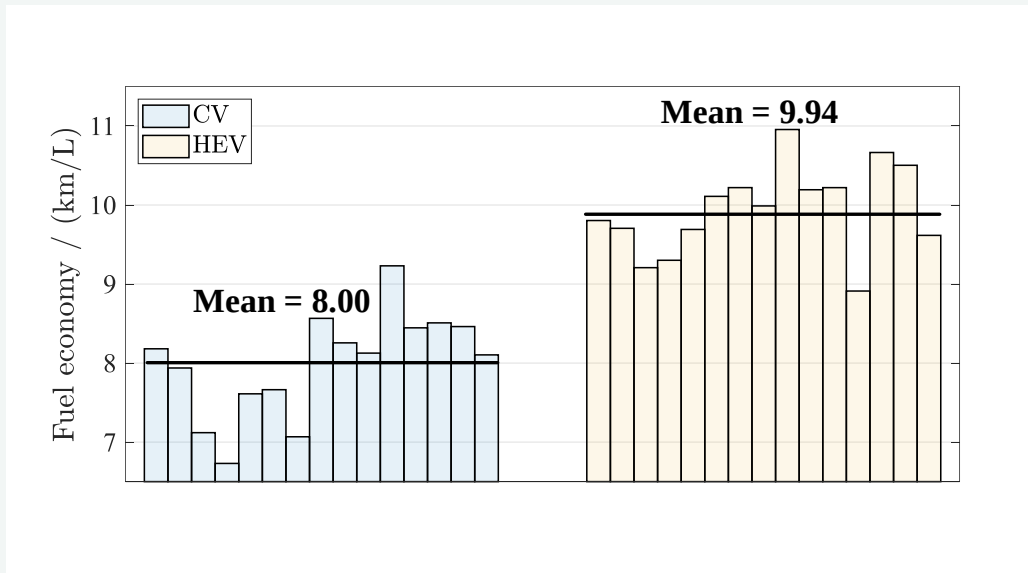
+31%
Fuel economy



Jeju logistics operation

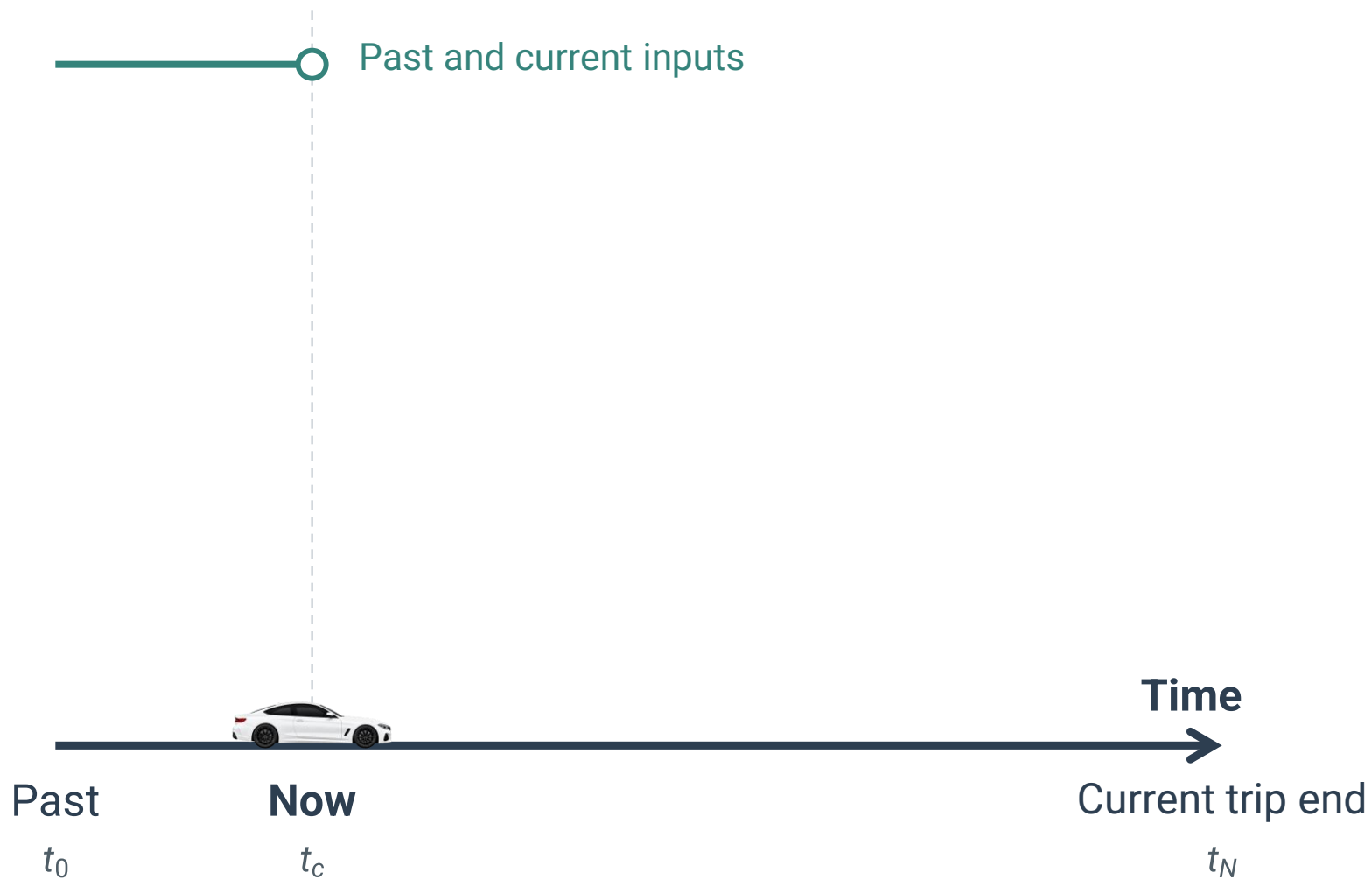


+24.3%
Mean, four vehicles



Driving information and preview horizon

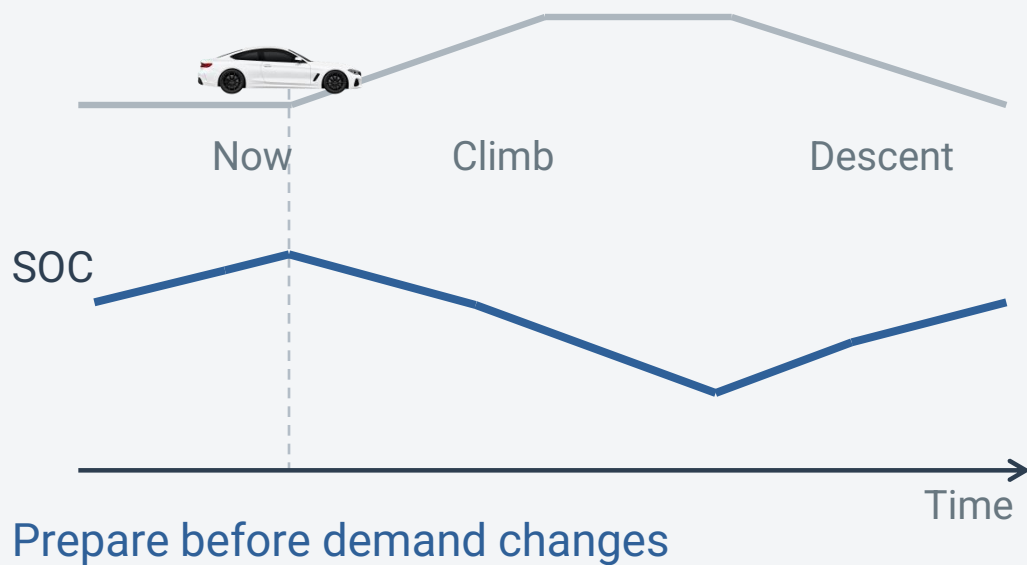
Causal EMS



Causal EMS: adaptation without preview

Idealized full-preview policy

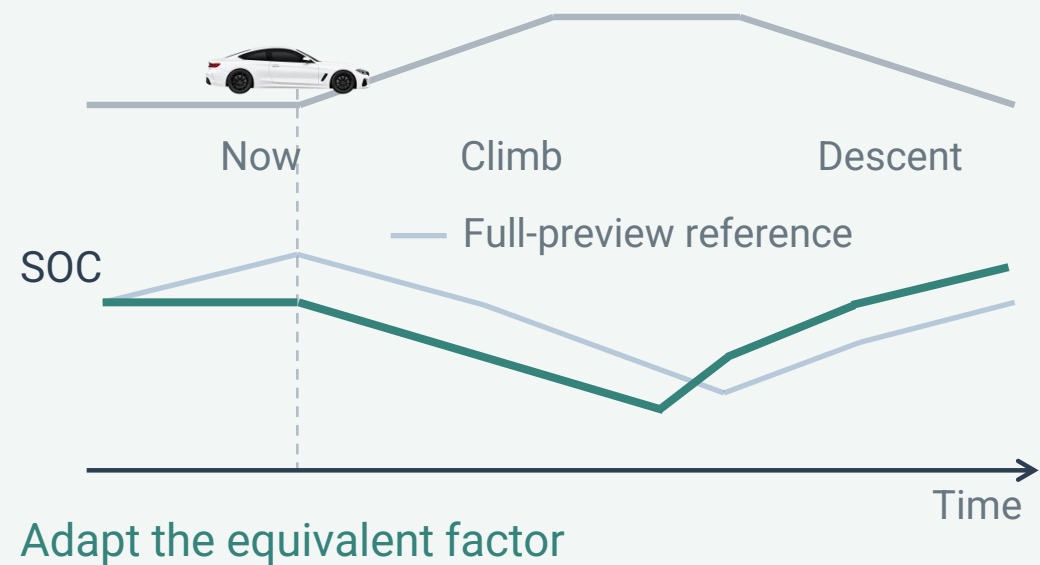
Upcoming terrain is available



Causal EMS Implemented in the conversion

A-ECMS-NO

Adaptation uses observed driving conditions



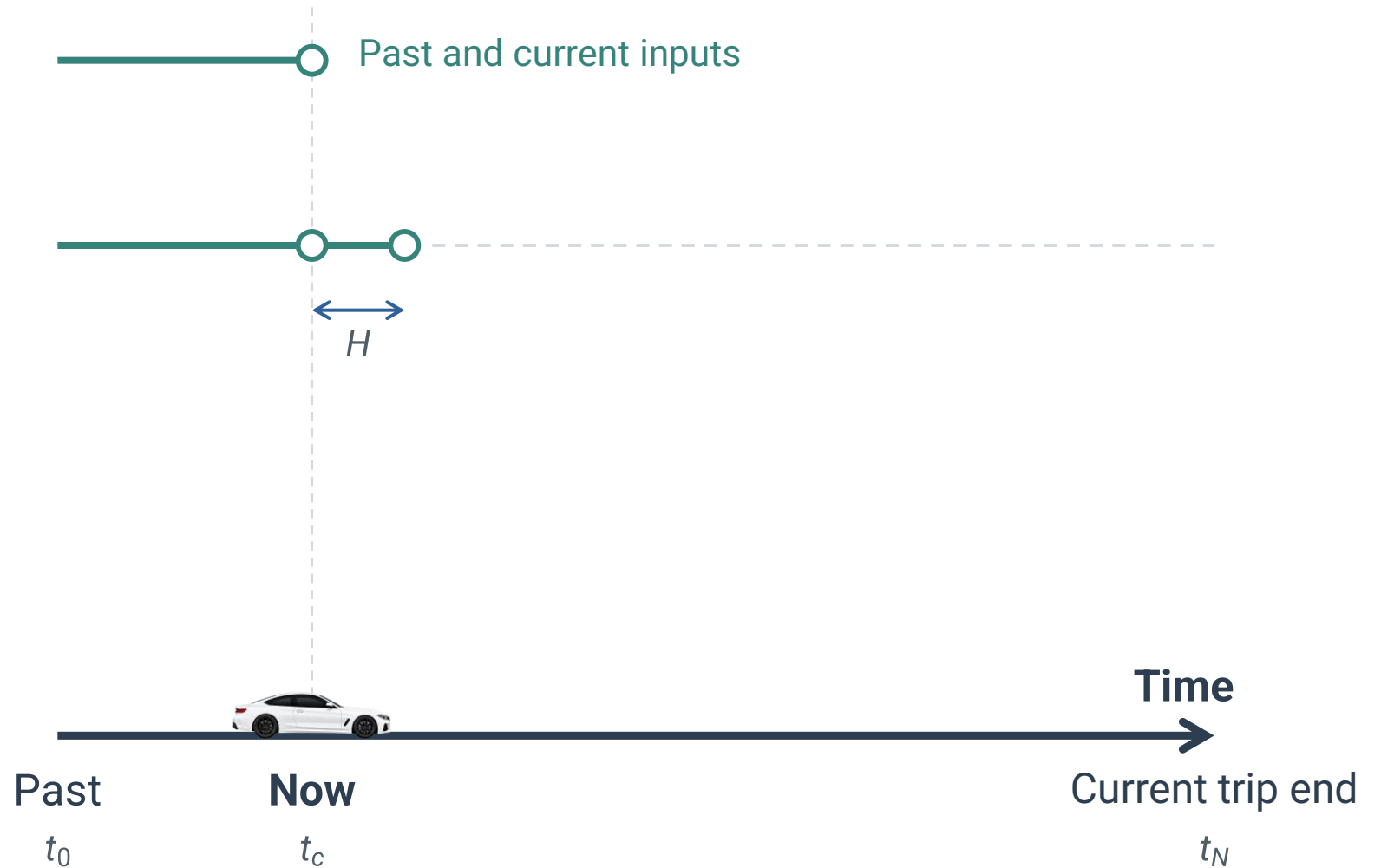
A-ECMS-NO adapts to operation **without directly previewing** future terrain.

Driving information and preview horizon

PEMS: predictive EMS

Causal EMS

Short-horizon PEMS



Short-horizon PEMS

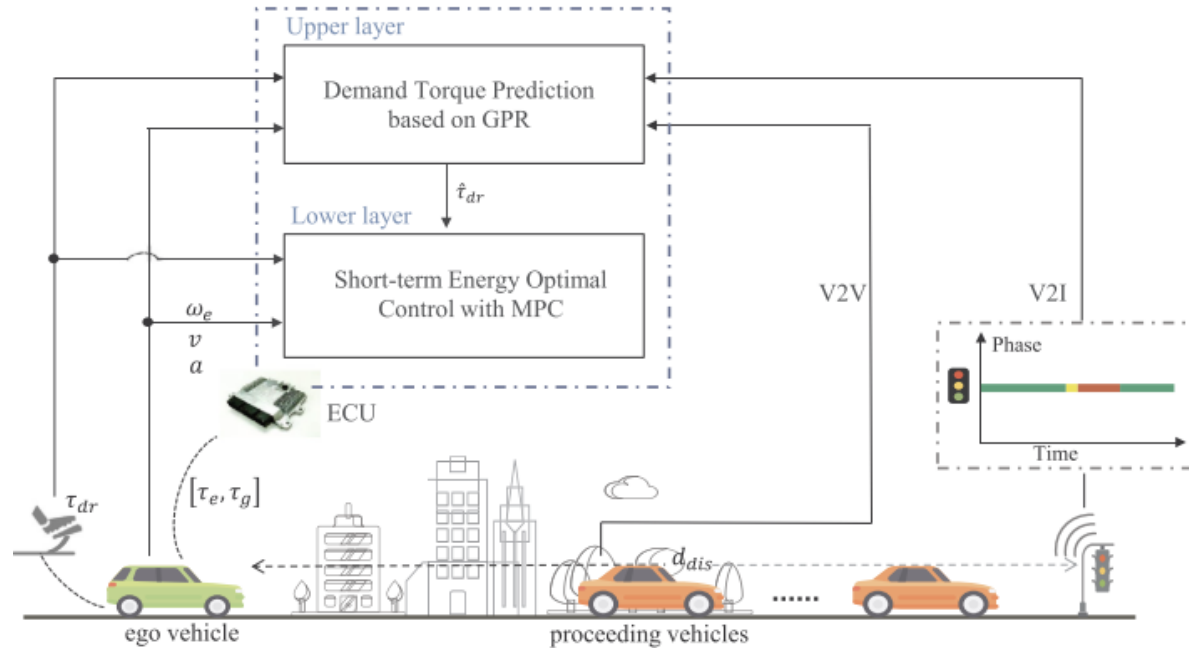


Fig. 1. The **connected** short-term energy management system with V2V and V2I.

Optimal control problem

$$\min_{T_{\text{eng}}(\cdot)} \int_{t_c}^{t_c+H} \dot{m}_f(T_{\text{eng}}(\tau), \tau) d\tau$$

Subject to vehicle and battery constraints

t_c : current time

H : preview duration

Apply the first control action.

Update the prediction and repeat.

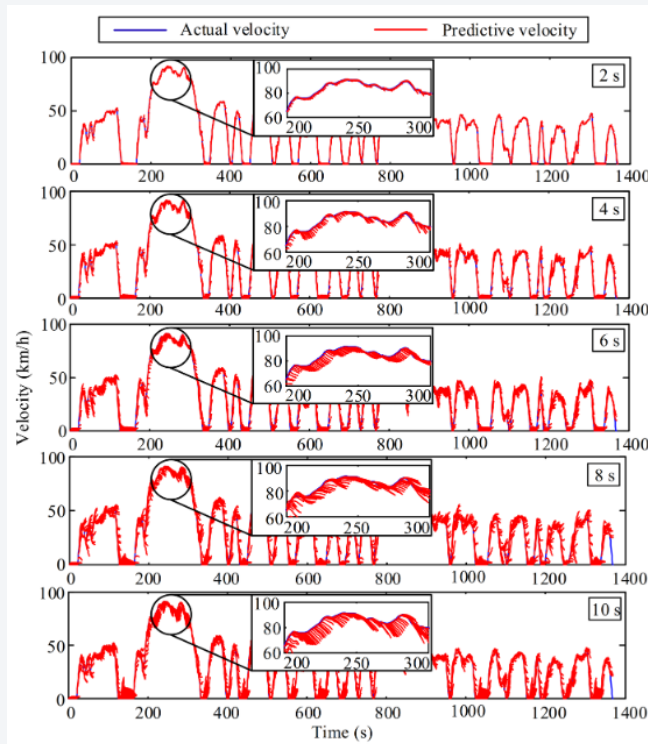
Connected predictive EMS example (Zhang et al.)

Predict upcoming demand and optimize over a **moving preview horizon**.

Prediction horizon: accuracy and control

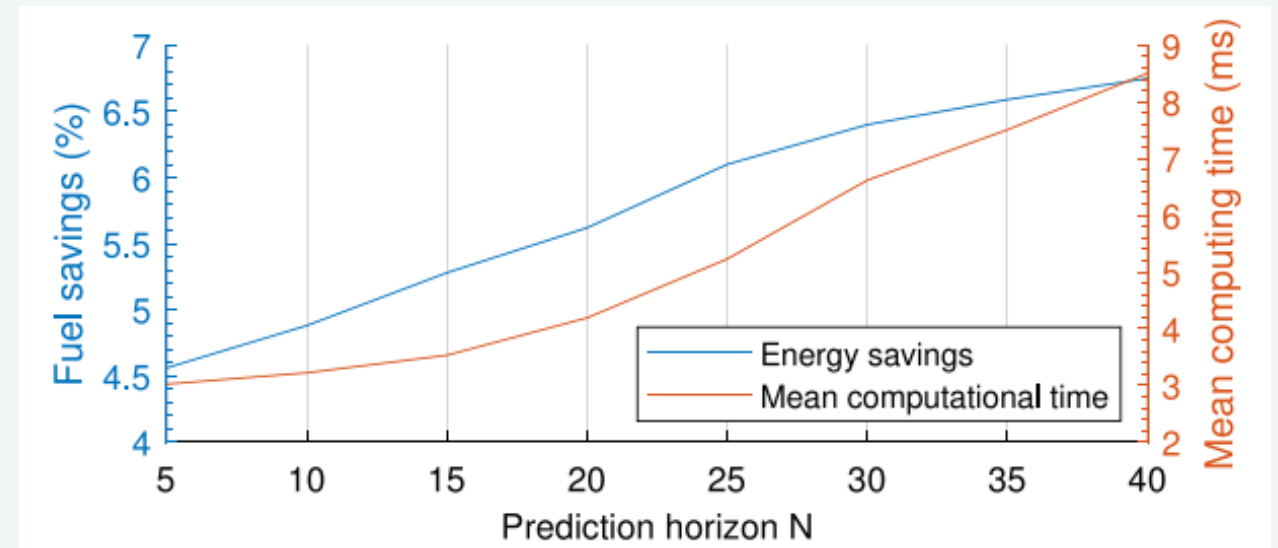
Prediction accuracy

Example: Lin et al., 2020



Fuel savings and computation

Horizon study: Ju et al., 2023



In this study, longer horizons increased fuel savings and computation.

Accurate short preview still covers only part of the trip.

Driving information and preview horizon

PEMS: predictive EMS

Causal EMS



Short-horizon PEMS



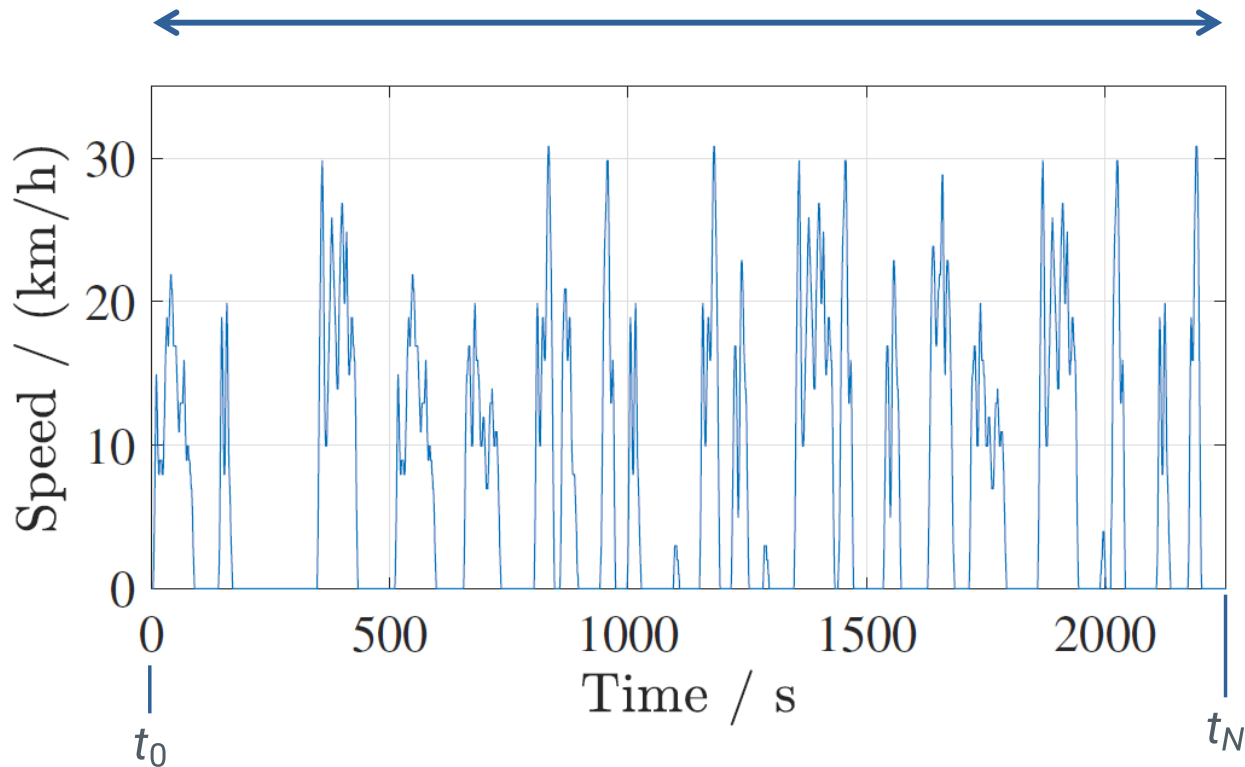
Full-horizon PEMS



Full-horizon control: a much longer OCP

Future driving trajectory

A detailed sequence through the trip end



Optimal control problem

Preview interval

Short: $[t_c, t_c + H]$

Full: $[t_c, t_N]$

$$\min_{T_{\text{eng}}(\cdot)} \int_{t_c}^{t_N} \dot{m}_f(T_{\text{eng}}(\tau), \tau) d\tau$$

$$\dot{x} = f(x, T_{\text{eng}}, \tau),$$

$$\underline{x} \leq x(\tau) \leq \bar{x}, \quad T_{\text{eng}}(\tau) \in \mathcal{U}(\tau),$$

$$x(t_c) = x_c, \quad x(t_N) = x_N.$$

Optimize the full control sequence

Direct prediction and optimization over a long trajectory are impractical in real time.

A road-link view of the full-horizon problem

Can we describe the same trip without predicting every time sample?

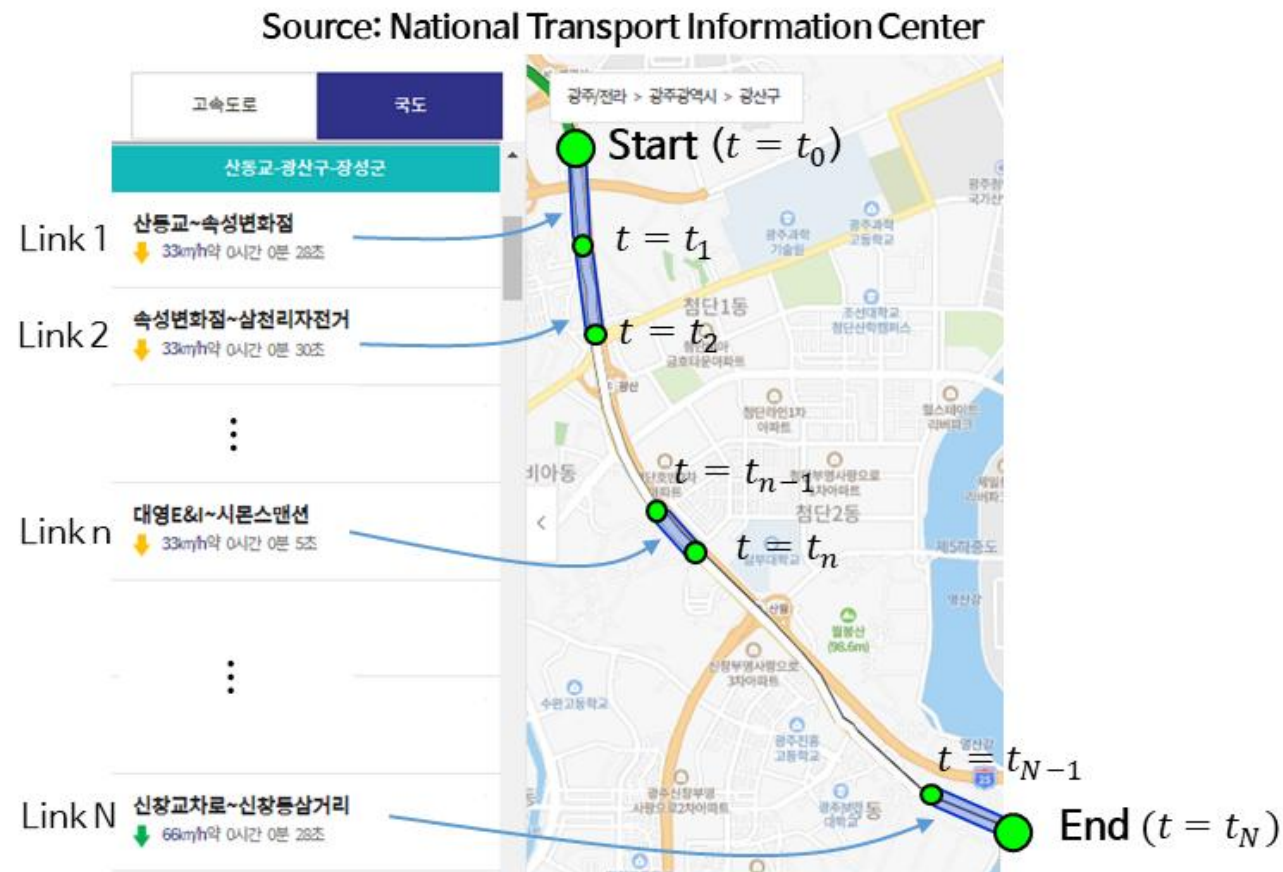
Thousands of time samples



Tens of road links



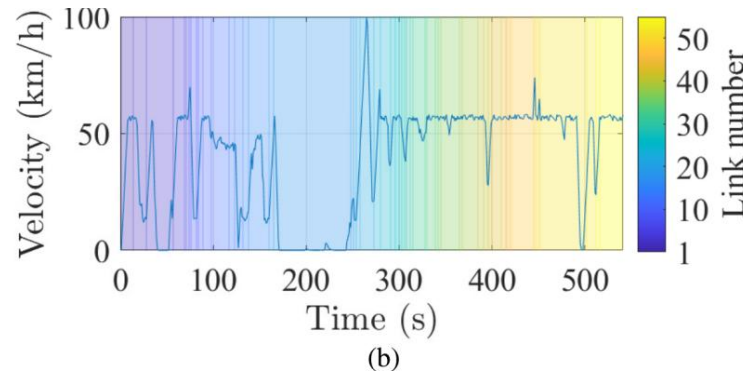
A macroscopic description of the same trip



Keep the trip horizon; change how future driving is described.

From time-domain control to link-based decisions

Time domain
About 550 s of driving



Link domain
55 road links

Time-domain problem

Decision: control-input sequence

$$\min_{u(\cdot)} \int_{t_c}^{t_N} \dot{m}_f(u(t)) dt$$

$$\dot{x} = f(x, u, P_{\text{dem}}),$$

$$\underline{x} \leq x(t) \leq \bar{x}, \quad \underline{u} \leq u(t) \leq \bar{u},$$

$$x(t_c) = x_c, \quad x(t_N) = x_N.$$



Principle of
optimality + PMP

Within-link
assumptions

Link-domain problem

Decision: one costate per road link

$$\min_{\lambda_1, \dots, \lambda_N} \sum_{i=1}^N J(\lambda_i, \theta_i)$$

$$x_i = x_{i-1} + g(\lambda_i, \theta_i),$$

$$\underline{x} \leq x_i \leq \bar{x} \quad (i < N),$$

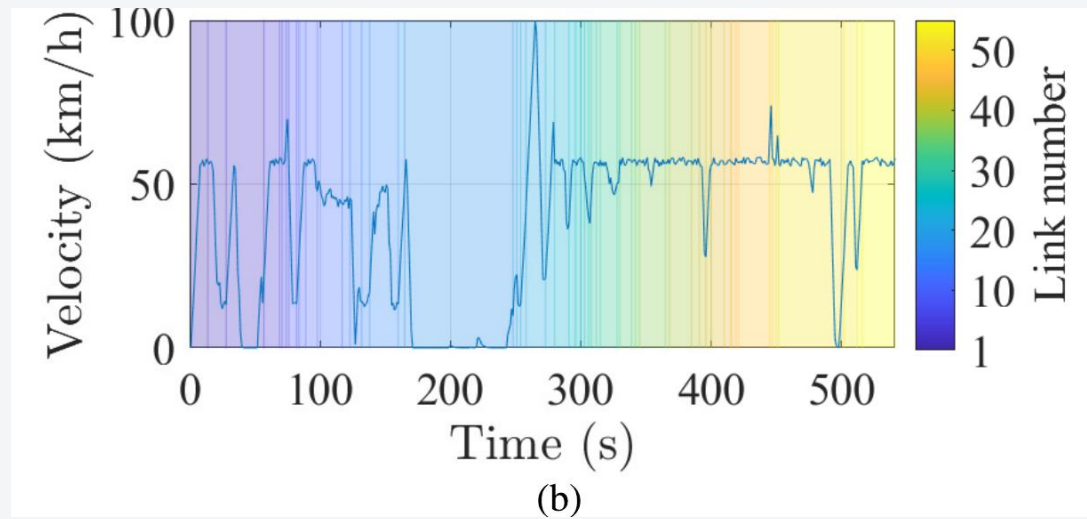
$$x_0 = x_c, \quad x_N \text{ prescribed.}$$

Optimize **link costates** and recover instantaneous power commands.

Reformulation reveals four link quantities

Time-domain prediction

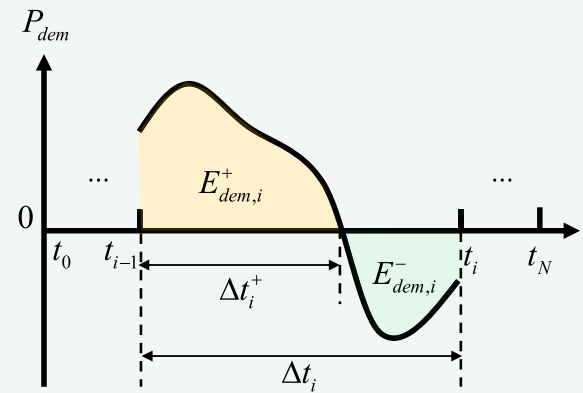
Driving profile



Speed + slope + vehicle model
→ power-demand trajectory

Link-domain prediction

Four quantities per link



Energy

$E^+_{dem,i}$, $E^-_{dem,i}$

Time

Δt_i , Δt_i^+

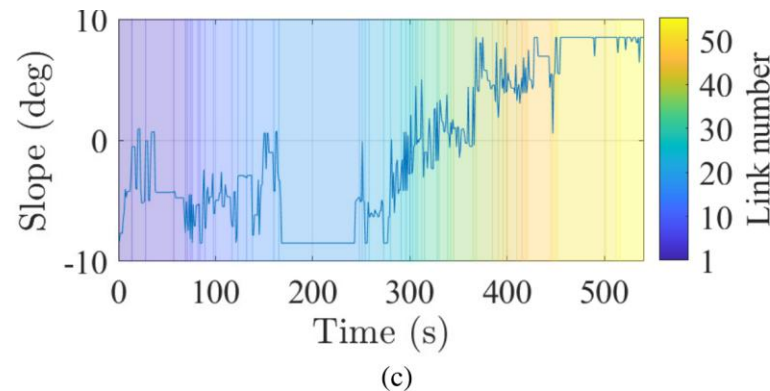
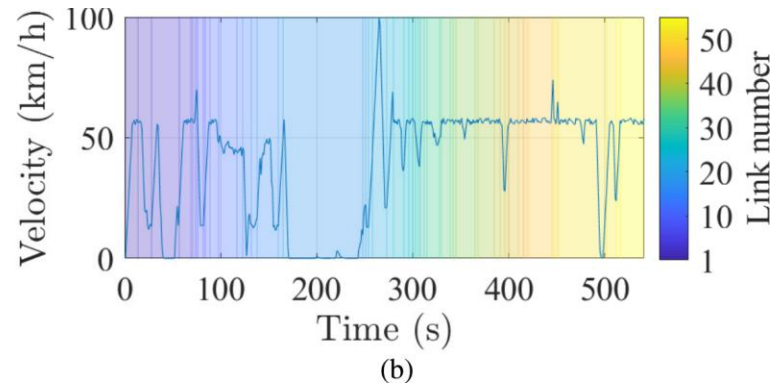
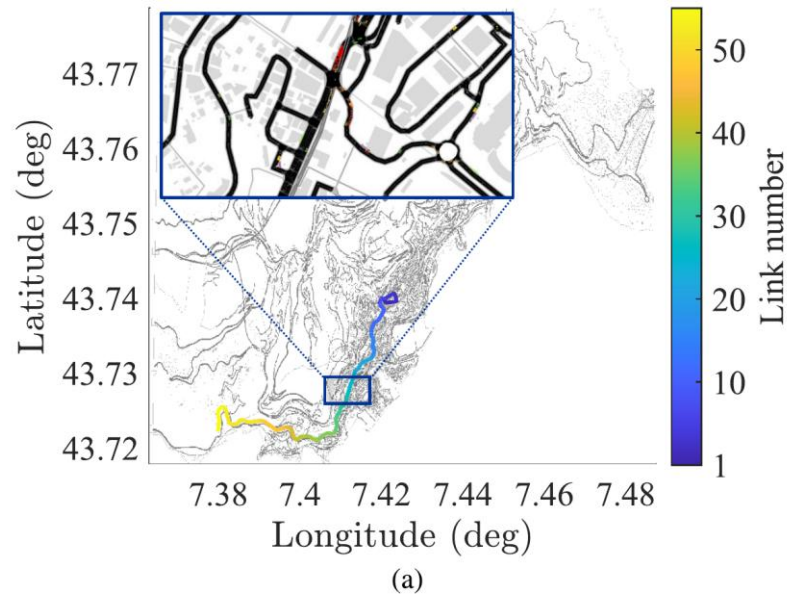
Energy: propulsion / braking

Time: total / propulsion

Predict link **energy** and **time** across the remaining trip.

Validation in the Monaco traffic network

A 55-link Monaco route is simulated in SUMO.



Vehicle model



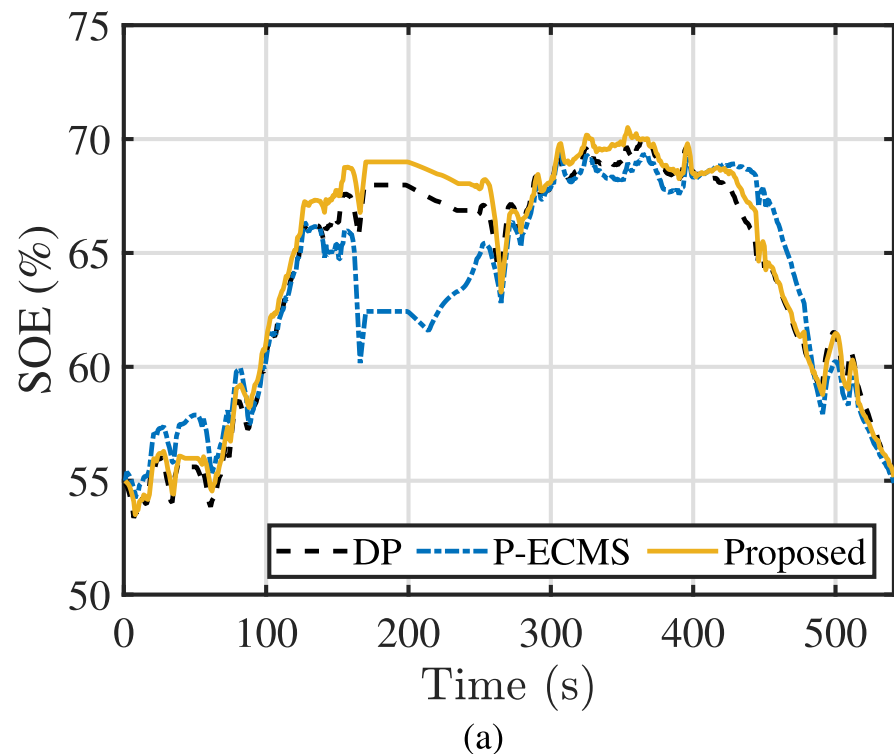
Hyundai NEXO FCEV
model simulated
in MATLAB

Comparison DP / Link-based PEMS (proposed) / P-ECMS (predictive baseline)

Known future link parameters are used to test controller feasibility.

Controller results under known future inputs

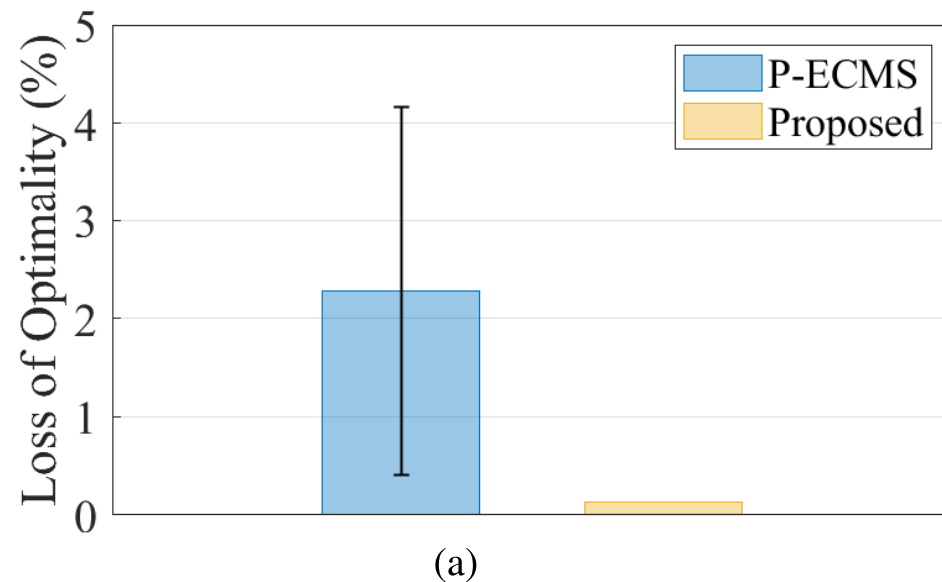
Battery energy trajectory



SOE: battery state of energy

Fuel comparison: matched final SOE. QP: ≤ 2 ms on the test PC; prediction excluded.

Loss of optimality



P-ECMS: mean $\pm$ std across tuning settings

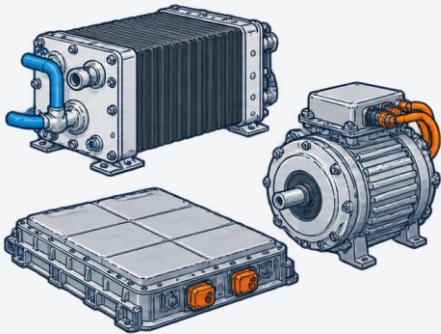
Proposed EMS: **0.14%** loss relative to DP

Extensions of xEV full-horizon control

Extend the link-based formulation to new objectives and dynamics.

Stack durability

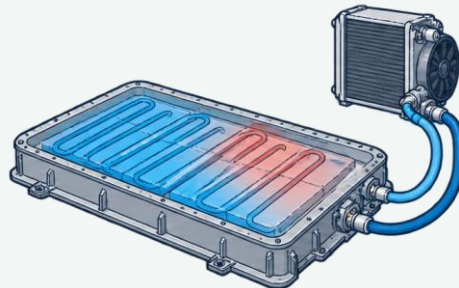
Hydrogen use +
stack degradation



Control: stack power
State: battery energy

Battery thermal control

Cooling energy +
temperature constraints



Control: cooling power
State: battery temperature

Eco-driving

Driving energy +
arrival-time requirement



Control: link travel times
Scope: current trip to destination

The required link quantities change with the control objective.

Link information depends on the control task

Energy management

Energy: propulsion / braking

Time: total / propulsion

Stack durability

Energy: net demand

Time: total



Battery thermal control

Energy · **Power**² integral

Time: total

Eco-driving

Speed variance
Signals

ITS / V2I + vehicle data & models → **link predictions**

Driving information and preview horizon

PEMS: predictive EMS

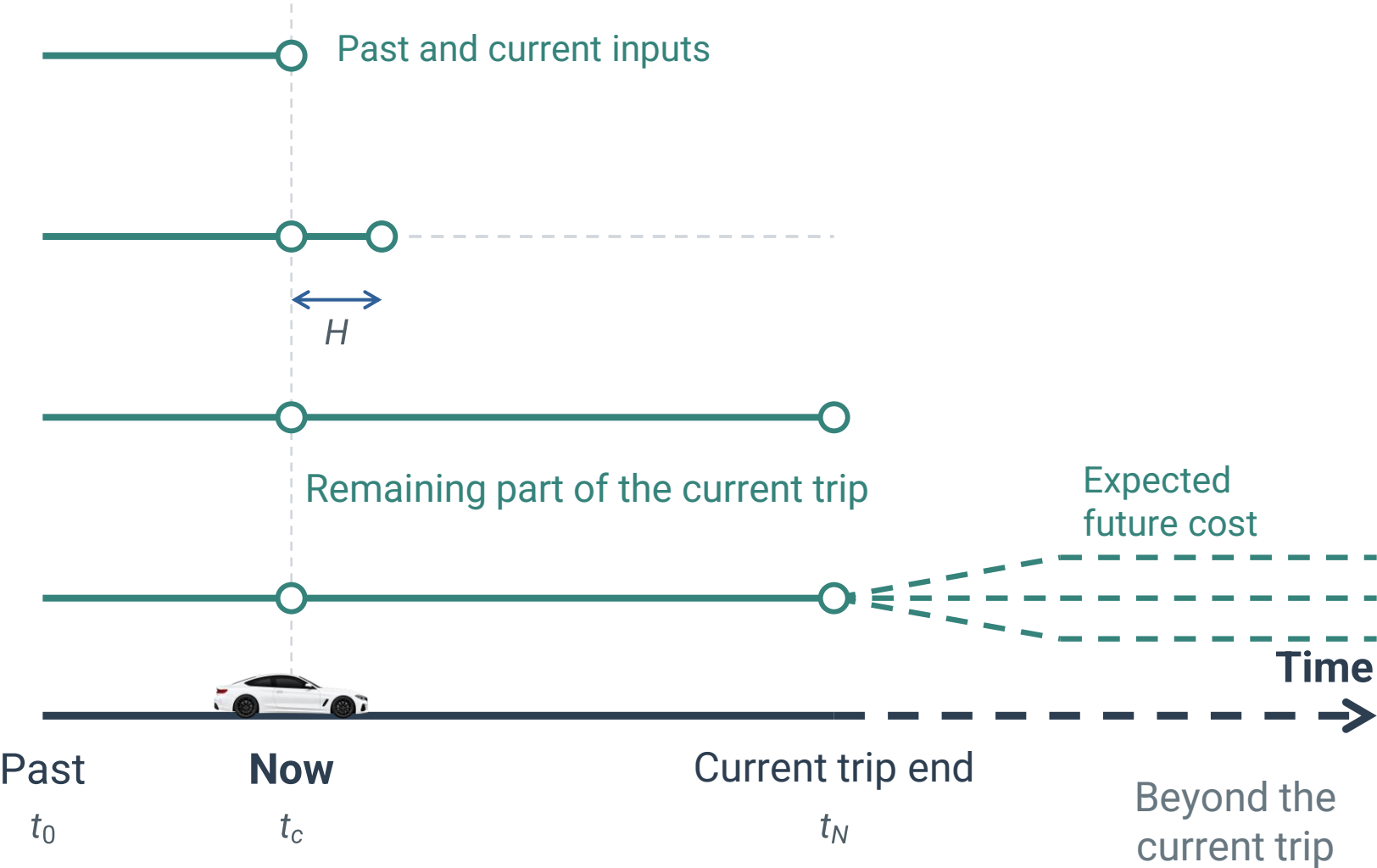
Causal EMS

Short-horizon PEMS

Trip-specific PEMS

Full horizon of the current trip

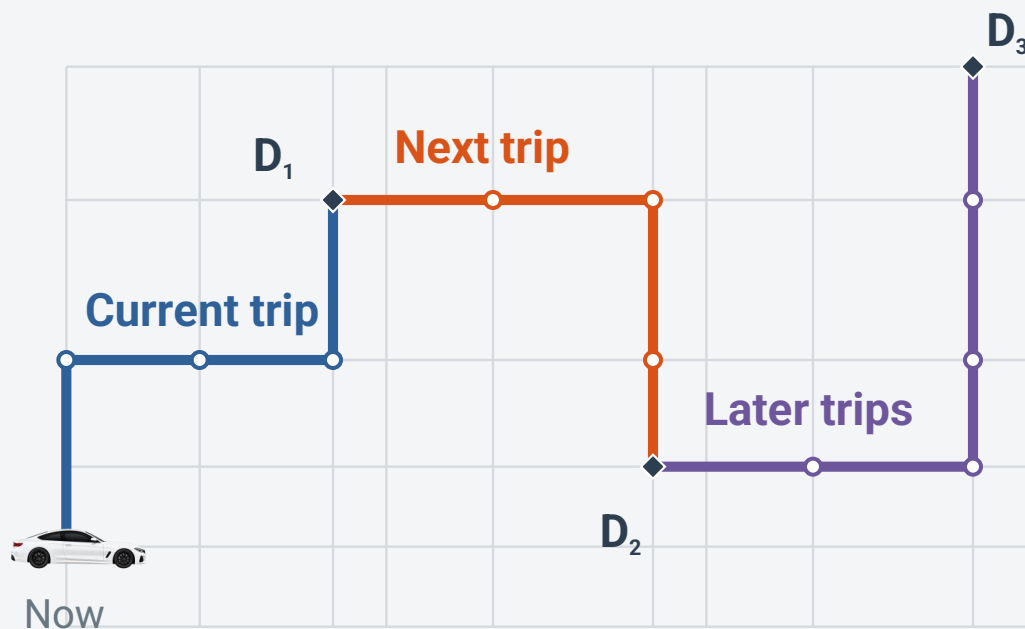
Network-aware PEMS



Successive trips in a traffic network

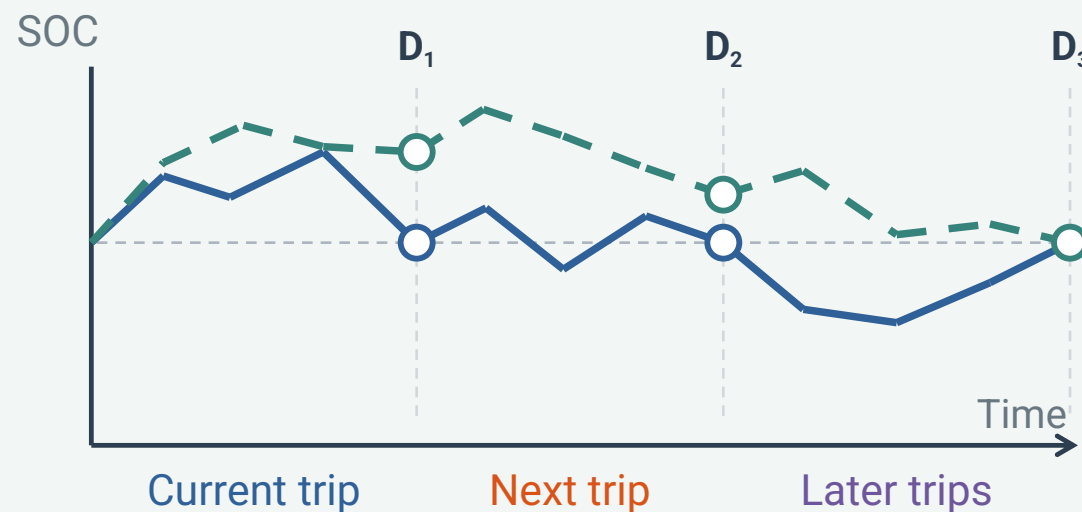
Trip-specific PEMS optimizes each trip up to its destination.

Network domain



Time domain

— Trip-specific PEMS
- - Network-aware PEMS



The SOC at each destination affects the fuel cost of later trips.

Energy management beyond the current trip

Trip-specific PEMS

Current trip only

$$\min_{u(\cdot)} \int_{t_c}^{t_N} \dot{m}_f(u(t)) dt$$

$$x(t_N) = x_{\text{ref}}$$

Fixed SOC at the current trip end

Network-aware PEMS

Current trip and subsequent operation

$$\min_{u(\cdot)} \left[\int_{t_c}^{t_N} \dot{m}_f(u(t)) dt + \hat{V}(x(t_N)) \right]$$

↑
**Expected fuel cost
beyond the current trip**

V uses network forecasts and future-trip destinations

Shared vehicle and battery constraints

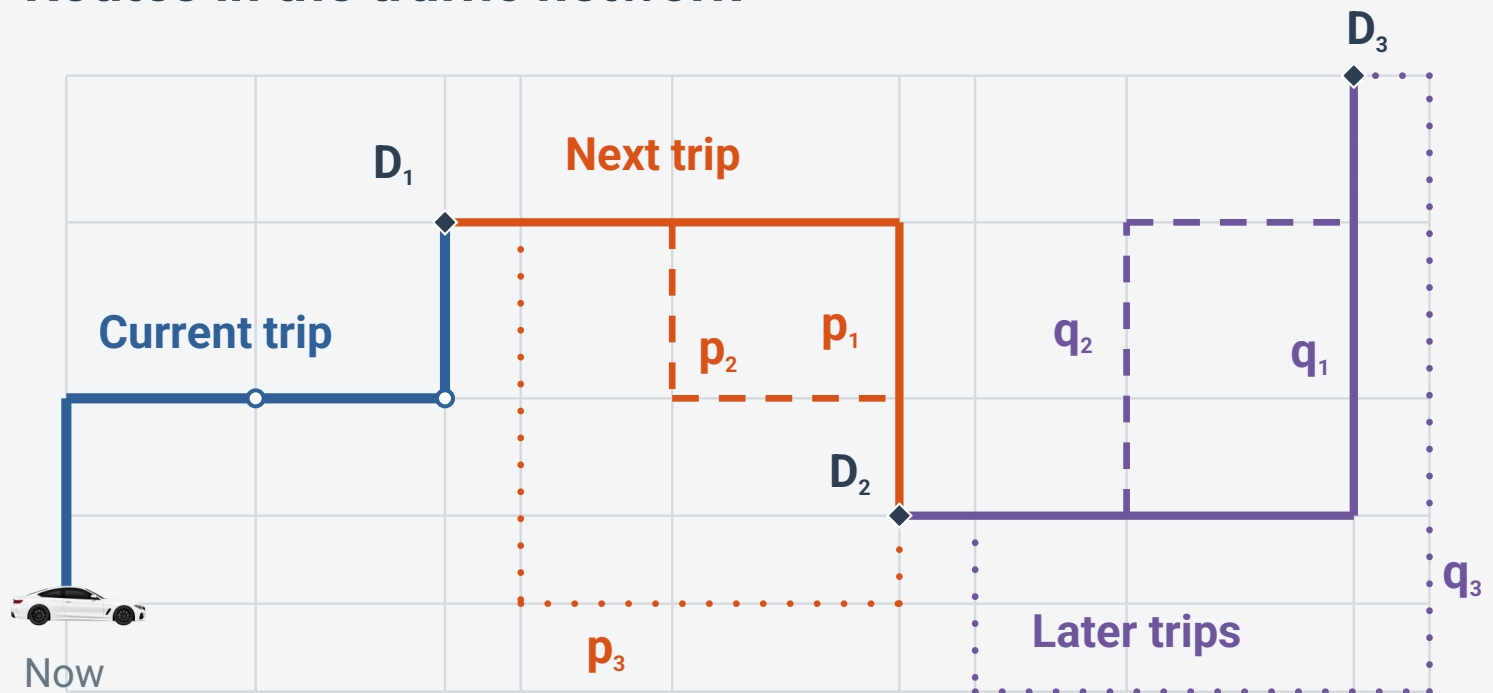
$$\dot{x} = f(x, u, P_{\text{dem}}), \quad \underline{x} \leq x(t) \leq \bar{x}, \quad \underline{u} \leq u(t) \leq \bar{u}, \quad x(t_c) = x_c$$

x: SOC u: fuel-cell power

Future routes and the expected fuel cost

Each trip has a known destination, while its future route may vary.

Routes in the traffic network



Route probabilities from predicted link travel times

Expected fuel cost

Next trip

$$\sum_r p_r J_{\text{next},r}$$

+

Later trips

$$\sum_s q_s J_{\text{later},s} + \dots$$



Beyond the current trip

$$\hat{V}(x(t_N))$$

Route probabilities weight future fuel costs, evaluated from the **current trip-end SOC**.

Link-domain formulation beyond the current trip

Time domain

Decision: control-input sequence

$$\min_{u(\cdot)} \left[\int_{t_c}^{t_N} \dot{m}_f(u(t)) dt + \widehat{V}(x(t_N)) \right]$$

$$\dot{x} = f(x, u, P_{\text{dem}}),$$

$$\underline{x} \leq x(t) \leq \bar{x}, \quad \underline{u} \leq u(t) \leq \bar{u},$$

$$x(t_c) = x_c.$$

Driving trajectory over the current trip



Principle of
optimality

+ PMP

+ Within-link
assumptions

Link domain

Decision: one costate per road link

$$\min_{\lambda} \left[\sum_{i=1}^{N_1} J_i(\lambda_i, \theta_i) + \widehat{V}(x_{N_1}) \right]$$

$$x_i = x_{i-1} + g(\lambda_i, \theta_i),$$

$$\underline{x} \leq x_i \leq \bar{x}, \quad \underline{\lambda} \leq \lambda_i \leq \bar{\lambda},$$

$$x_0 = x_c.$$

Energy and time for each road link

The future-cost term remains in the link-domain representation.

Validation in the Monaco traffic network

SUMO supplies traffic for the Monaco network.



Known destinations for future trips and perfect link-parameter predictions

Common final SOC is imposed for all comparison methods.

MIGHTY FCEV model



Mass 4,495 kg · Fuel cell 90 kW
Motor 140 kW · Battery 21.0 kWh

Driving scenario: **5 trips**
Update and re-planning: **300 s**

What the four comparison methods optimize

Optimization scope

○ Link boundary | Trip boundary

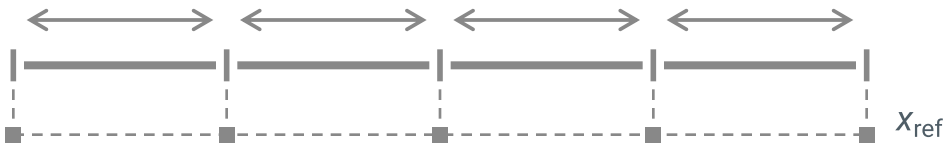
Information and SOC condition

Offline DP



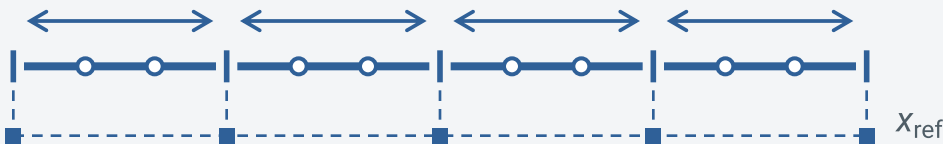
Full future known
One optimization

Trip-specific DP



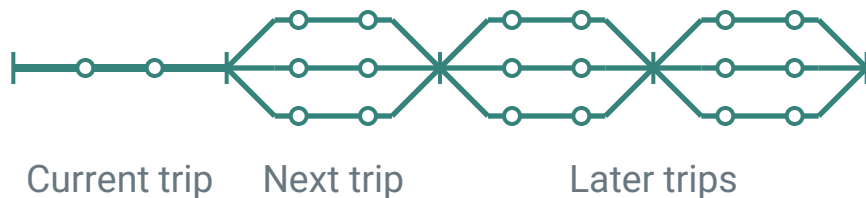
Current trip only
Fixed trip-end SOC

Trip-specific link PEMS



Link-based current trip
Fixed trip-end SOC

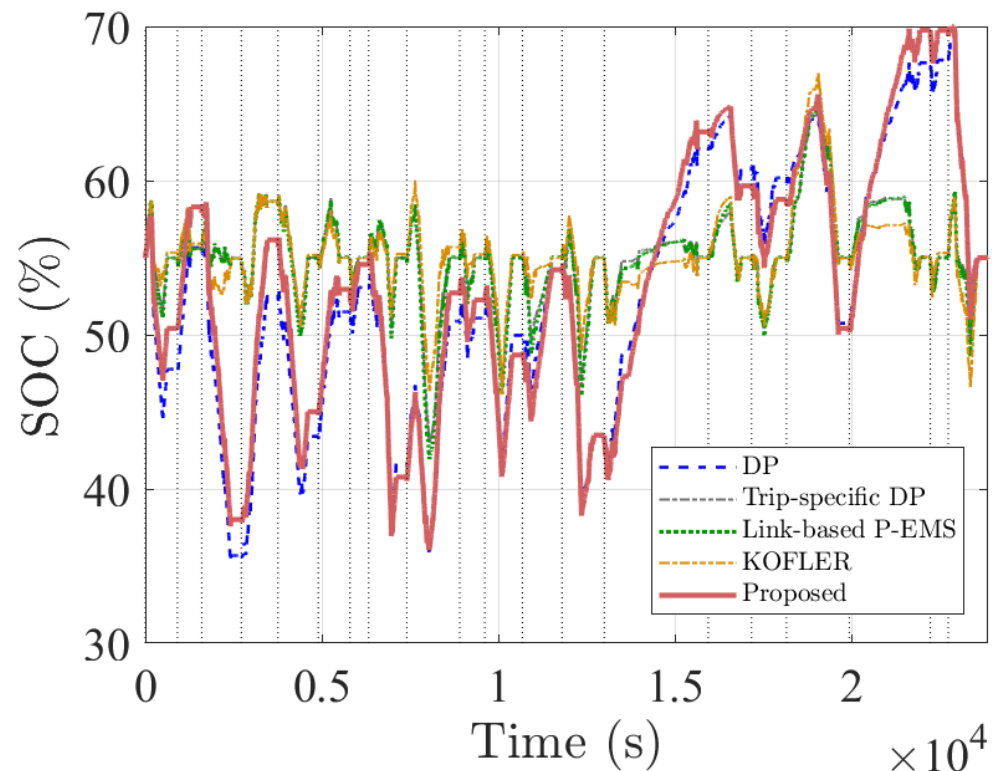
Proposed



Route probabilities
Expected future cost
Adaptive trip-end SOC

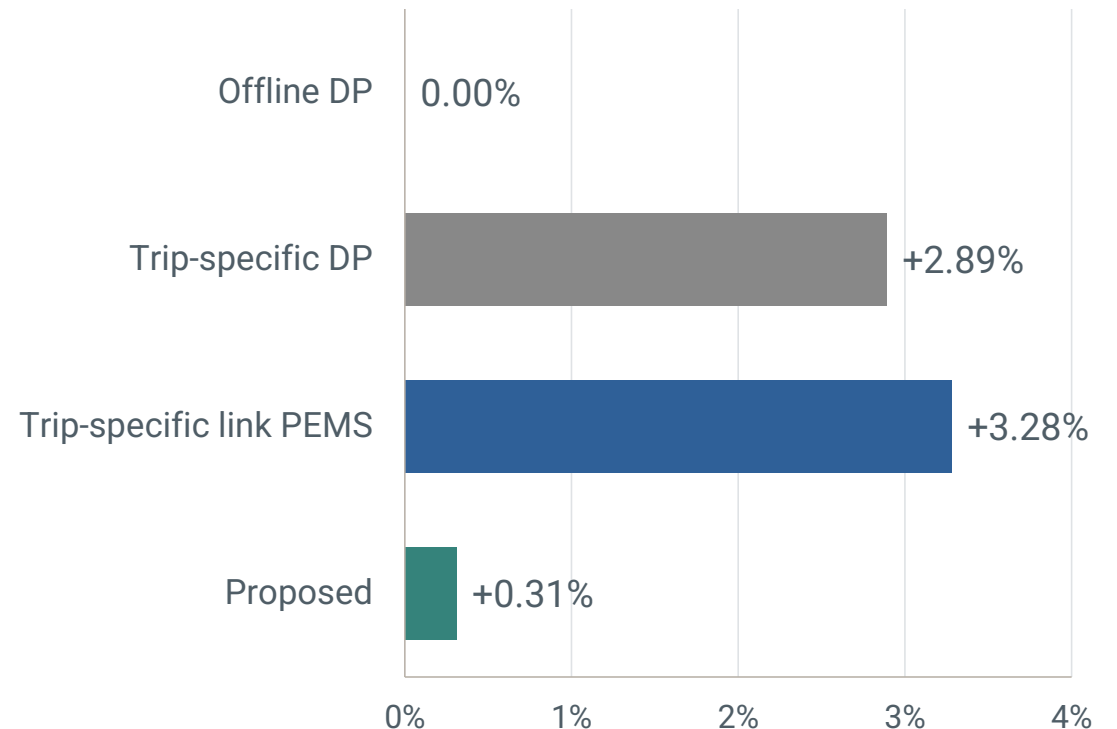
Network-aware EMS: SOC allocation and fuel use

SOC across successive trips



Intermediate SOC targets reflect later operation.

Excess fuel use vs. offline DP



Matched final SOC; exact link parameters

Proposed EMS: 0.31% more fuel than offline DP in the five-trip simulation.

Key takeaways

Energy decisions need a longer view.

Causal adaptation, trip-specific preview, and operation beyond the current trip.

Road links make long-horizon control tractable.

Predict link quantities. Account for future trips through expected fuel cost.

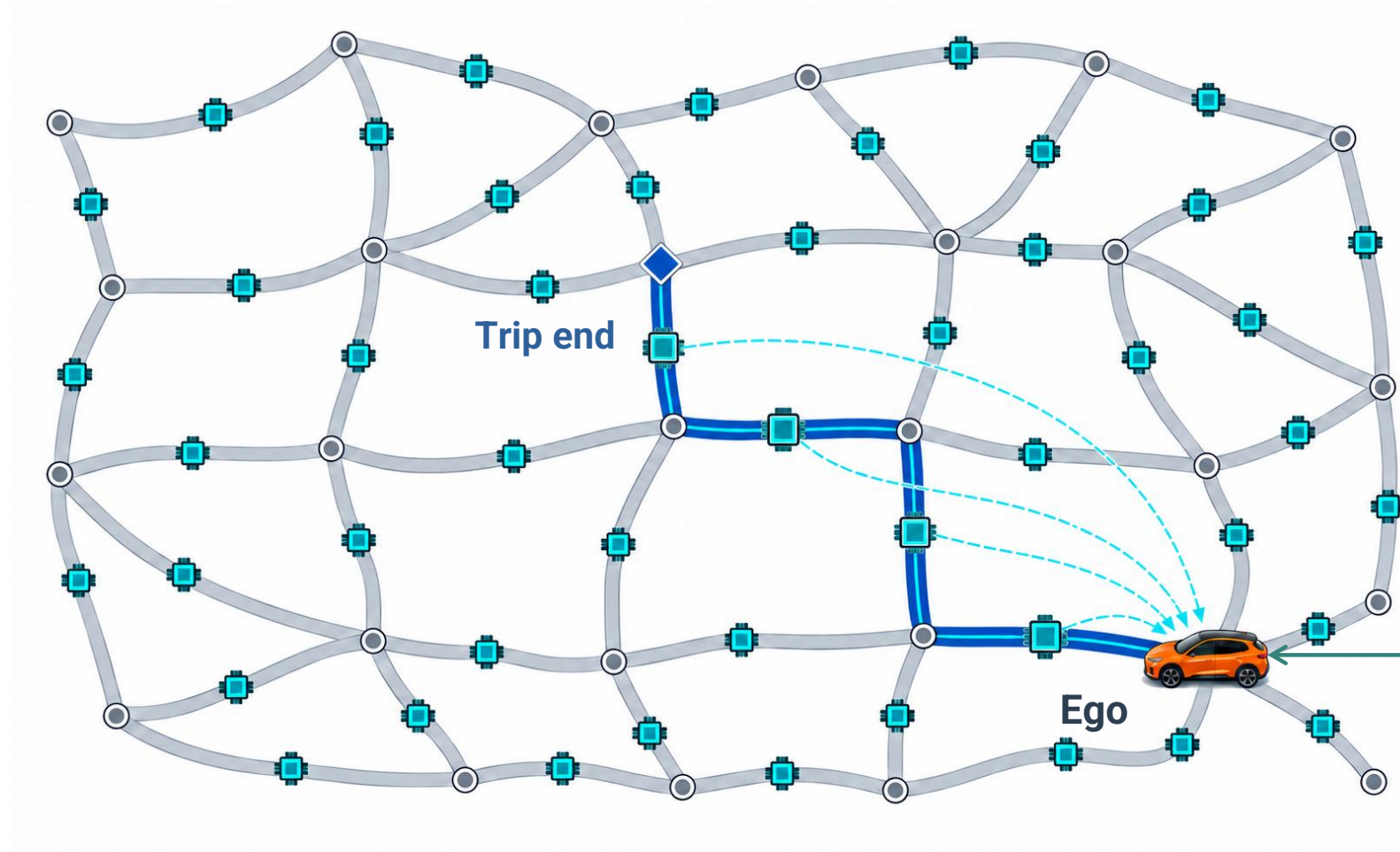
Simulation supports the feasibility of network-aware EMS.

The next step is reliable link information and integrated vehicle validation.

Toward network intelligence through industry–academic collaboration.

Network intelligence: the current trip

Every current-trip link informs the ego



Link-level edge computing



Receive
via RSU

Estimate
and store



Time



Energy



Speed
variance

V2I

Each chip: link-level edge computing

Network intelligence: beyond the current trip

Link forecasts support current and future trips

