Introduction to the 2023 Benchmark Challenge on Energy Optimal Control of Connected EVs

Abstract

With the possibility to use emerging intelligent connectivity information and increasing computational power, extensive studies on advanced energy optimization control schemes have been conducted for improving the energy economy of connected and automated vehicles (CAVs). In this document, aiming at reducing the energy consumption of electric vehicle (EV) under V2X connected environment, a benchmark problem proposed by 2023 CVCI Committee is introduced. It is assumed that the targeted vehicles are in the connected environment with real-time connected information, which is obtained through a commercial traffic simulator. Moreover, a high-fidelity, industrial-level plant model of a pure EV with a physics-based automotive air conditioning (A/C) system is provided for challengers. The task of the benchmark is to design a controller that matching the passenger comfort requirements and achieving the improvement of fuel economy while satisfying the constraints of the driving safety and travel time.

1 Introduction

Vehicle electrification supplies an efficient path to reduce the dependence on fossil fuel energy, and electric vehicles (EVs) dominate the development trend among all feasible solutions. Moreover, the real-time communication in connected and automated vehicles (CAVs) through vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V) and advanced sensors provides the look-ahead preview of traffic conditions and opens up unprecedented opportunities for enhanced safety, mobility, and energy efficiency, particularly for EVs. In particular, CAVs can develop eco-driving and route planning strategies to improve the powertrain system efficiency by exploiting increased situational awareness gained from sensory data.

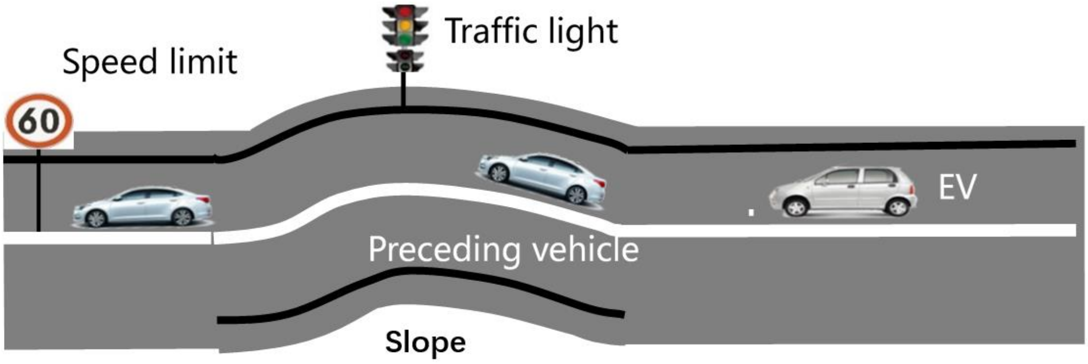


Figure 1: Potential for energy saving under V2X connected environment

Eco-driving can be realized via several aspects including moderate acceleration, anticipation of traffic flow and signals and smoothing the velocity profile according to the road topography. For instance, slowing down prior to a steep descent and increasing speed during the descent reduces energy loss, since the potential energy at the top of the hill can be translated to kinetic energy, while maintaining road speed limits without excessive braking.

In addition, besides the power consumed for traction, the power consumed for climate regulation, such as air conditioning (A/C) system, represents significant auxiliary load in the summer time and significantly impact the overall vehicle energy economy. This calls for advanced control strategy which is able to jointly optimize the power and thermal loads for EVs for improved energy efficiency.

Aiming at challenging the next generation vehicle-level powertrain optimization and thermal management for EVs under the connected environment, a benchmark problem is put forward for students and researchers who work with vehicle optimal control in the 7th CVCI, Changsha 2023. The benchmark issues will be presented in the following section, and the provided simulation testing platform with its technical parameters will be explained in detail. Additionally, evaluation method for benchmarking results will be presented, and the schedule of the benchmark competition of CVCI 2023 can be found on *http://www.ascl.jlu.edu.cn/vci/cvci2023/Benchmark.htm.*

2 Benchmark Problem

Due to the limitation of battery capacity and energy density, the cruising range of

EVs is relatively short. The number of charging station is also far less than that of gas stations, making it inconvenient to charge EVs. Therefore, there is still the issue of "range anxiety" when driving an EV, especially using air conditioning (A/C) system simultaneously in the summer time. With the development of intelligent network technology, connected EVs can obtain real-time traffic environment information by using their own on-board sensors and V2X communication. How to use this information to optimize the energy consumption of electric vehicles and realize energy-saving control under real traffic flow is still an important technical challenge.

2.1 Energy-saving optimization control problem based on speed planning and power distribution

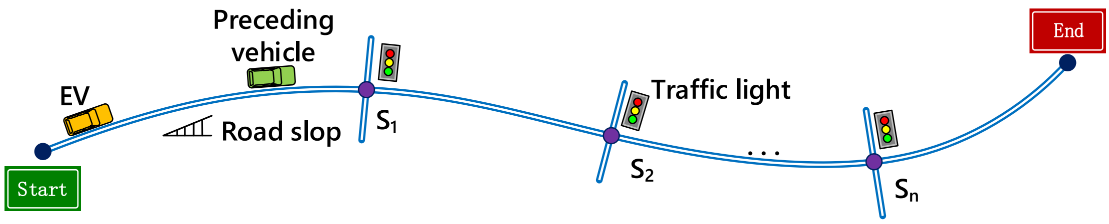


Figure 2: Energy-saving optimization control problem based on speed planning and power distribution

Connected EVs can obtain forward traffic information and road slope information based on on-board sensors and V2X communication. The main goal of this challenge is to realize comprehensive energy saving of EVs under real traffic flow through control algorithm design.

We selected urban and suburban roads which distinguish each other with different average traveling speed. The traffic flow of the roads under different flow rates is obtained through commercial software simulation. In this challenge, we provide vehicle models, traffic models and V2X models. Challengers are required to propose advanced control and optimization algorithms based on these models to achieve optimal energy consumption control of EVs.

The basic problems of energy saving and optimization in this challenge are shown in Fig. 2:

(1) There are five traffic scenes provided for simulation. The total length of each road is between 5 and 20 km, with different number of intersections on each road. Each

intersection has a pre-set reasonable timing of traffic lights.

(2) The traffic flow of the above urban roads at different time periods and under different flow rates is simulated in the traffic simulation software. In order to simplify the problem, one virtual vehicle is set in front of the ego EV, which is used to reflect the speed limit of the ego EV by the traffic flow. The ego EV is not allowed to overtake and collide with the front vehicle. Otherwise, points will be penalized or the score will be cancelled according to the specific situation.

(3) The elevation and slope information of urban roads are provided to investigate the impact of slopes on energy-saving control.

(4) In order to investigate the impact of traffic lights on energy-saving control, the current phases of the two traffic lights in front of the ego EV and the remaining time to switch to the next phases are provided in the traffic model. The ego EV must pass traffic lights in accordance with traffic rules. Violation of traffic rules will result in penalty points or cancellation of the challenge.

(5) The control algorithm needs to take into account both energy saving and road traffic efficiency. The ego EV must reach the destination within a certain period of time after the front vehicle reaches the destination. Otherwise, points will be penalized or the score will be cancelled depending on the specific situation.

(6) A four-wheel hub-drive EV is provided as the plant model for this Benchmark Challenge. Since the lateral motion and stability control of the ego EV is not considered, there is no differential input torque to the left and right side wheels, but the input torques of the front and rear in-wheel motors can be arbitrarily controlled. Challengers can achieve energy-saving control by optimizing the torque distribution between the front and rear in-wheel motors.

Based on the above rules, challengers are required to develop appropriate control algorithms to achieve energy optimal control through reasonable vehicle speed planning and motor torque distribution.

2.2 Energy-saving optimization problem considering both air-conditioning load and vehicle motion

In the hot summer, the energy consumption of the air conditioning system occupies a considerable part of the energy consumption of the EV. This is also one of the important factors for the "range anxiety" of EVs in practical use. On the premise of ensuring the comfort of passengers, it is also an important energy-saving way for EV by dynamically optimizing the cooling capacity and air supply volume of the air conditioning system, according to the changes of the vehicle states and the temperature of the cockpit. Therefore, the impact of hot summer weather on EVs will be considered under some working conditions in this challenge. Based on the selected actual traffic flow, the comprehensive energy consumption of EVs should be investigated. within the temperature range set of the passenger compartment. Challengers need to propose air-conditioning control algorithms to optimize vehicle energy consumption considering the actual driving conditions of electric vehicles.

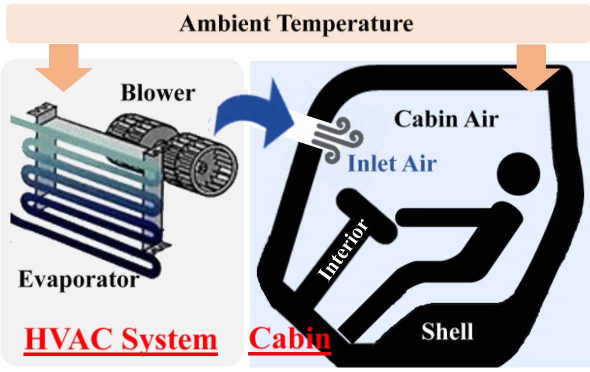


Figure 3: Schematics of the thermal system consists of HVAC system and cabin.

In this benchmark, the provided high fidelity thermal system simulation model of the targeted EV has been established based on CoolSim which is an open-source modeling environment available from the National Renewable Energy Lab (NREL). As shown in Fig.3, the considered thermal system includes the cabin and the heating ventilation and air conditioning (HVAC) system. The HVAC system includes the blower and the evaporator as part of the A/C system, whose power consumers are supplied by the battery pack. The mass flow of the cabin inlet air is adjusted by the blower and the evaporator is used to cool the cabin air. The control scheme proposed by the challengers should adjust the cabin temperature and manage the power consumption at the same time. The detailed constraints and models will be presented in the following sections.

3 Provided Simulation Platform

3.1. Simulator

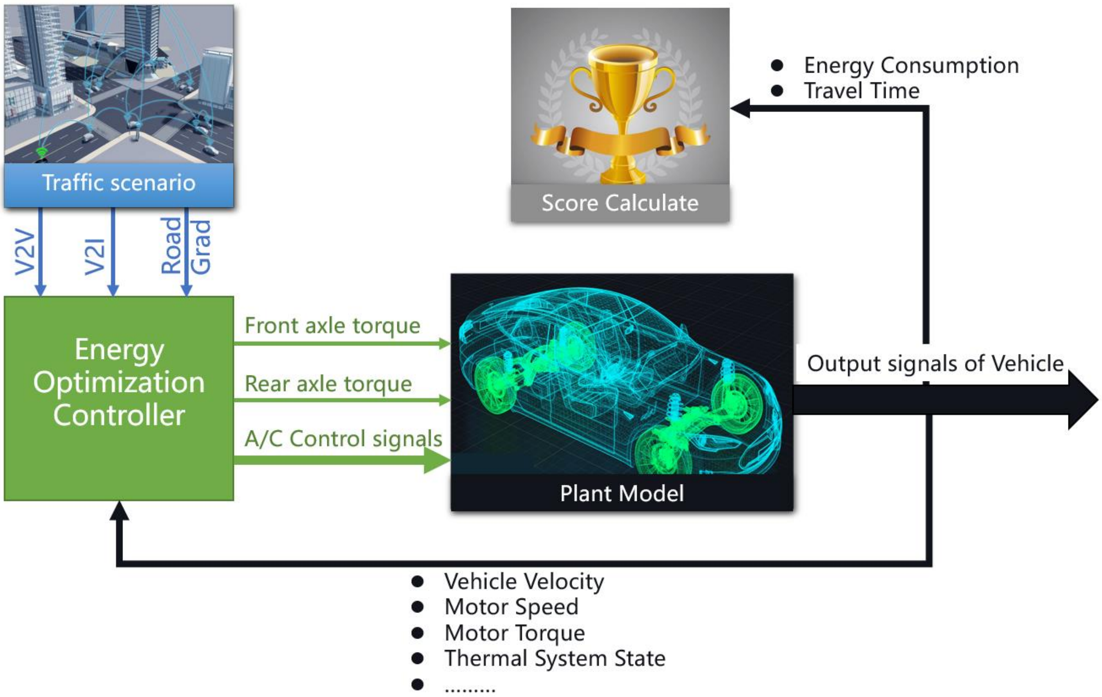


Figure 4: Control block diagram of the energy optimum controller

As shown in Fig. 4, the Challenge aims to promote the energy optimization research based on full electric vehicle with V2X technology involved. Compared to fuel vehicle the A/C system contribute to substantial amount of energy consumption, so the design of A/C control law is also considered in the challenge. The *Traffic Scenario* block includes V2I and V2V, through which challenger is able to get the traffic light information, the kinetic states of preceding car and road grad information, please check the detail introduction in chapter 3.3. The *Energy Optimization Controller* need to be updated by the challenger with front axle torque signal, rear axle torque and A/C system control signals as output. The *Plant Model* is built based on four-wheel drive electric vehicle, and the torque signal of front axle and rear axle is halved respectively before implemented to the four in-wheel motors. All the output signals of *Plant Model* are available for the challenger to utilize, please check the detail information in chapter

3.1.1. Overview of Simulator

The overview of the simulator is shown in Fig. 5, which mainly consists of three blocks: the Traffic Scenario, the Controller and the Plant Model, where the controller block is free for challengers to equip their own control scheme.

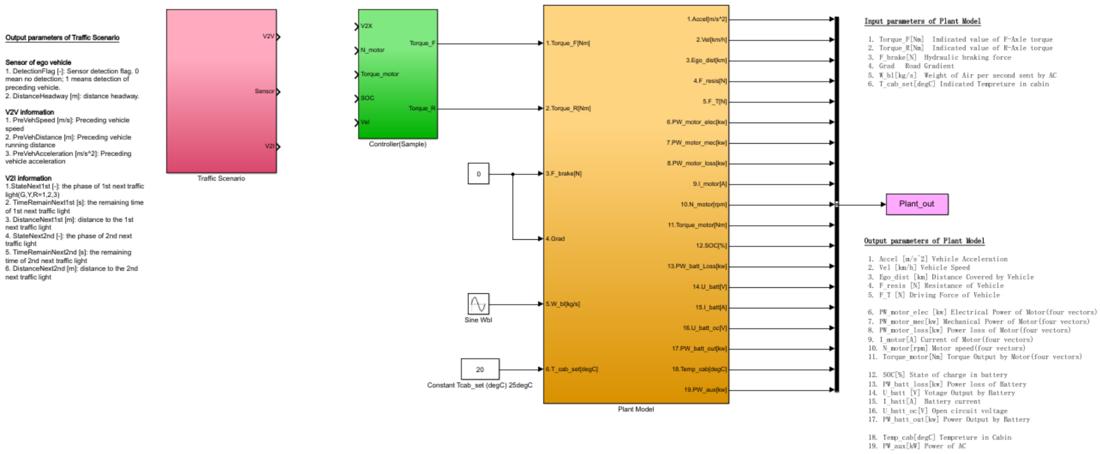


Figure 5: The overview structure of provided simulator

3.1.2. Plant model

The vehicle model is built based four-wheel driving electric vehicle, it is noted that the powertrain, auxiliary and vehicle are combined in an encrypted module named as *Plant Model* and the challengers cannot open it. It is noted for the challengers that this simulator can only run in MATLAB 2020b. The inputs of this module are the outputs of the controller designed by the challengers as listed in Table. 1. The detail descriptions of output signals of *Plant Model* are listed in Table. 2.

In the *Plant Model*, A/C model is also embedded for energy-optimization. The input and output of A/C are bus-signals listed in Table. 3, and detailed description of A/C system is stated in chapter 3.2.2.

Table 1: Input parameters of Plant Model

Parameter	Description	Unit
Torque_F	Indicated value of F-Axle torque	Nm
Torque_R	Indicated value of R-Axle torque	Nm
F_brake	mechanical braking force	N
Grad	Road gradient	--
A/C_Input	Control signals of A/C (three vectors)	--

Table. 2 Output parameters of Plant Model

Parameter	Description	Unit
Accel	Vehicle acceleration	m/s^2

Vel	Vehicle speed	km/h
Ego_dist	Distance covered by vehicle	km
F_resis	Resistance of vehicle	N
F_T	Driving force of vehicle	N
PW_motor_elec	Electrical power of motor(four vectors)	kW
PW_motor_mec	Mechanical power of motor(four vectors)	kW
PW_motor_loss	Power loss of motor(four vectors)	kW
I_motor	Current of motor(four vectors)	A
N_motor	Motor speed(four vectors)	rpm
Torque_motor	Torque output by motor(four vectors)	Nm
SOC	State of charge in battery	%
PW_batt_loss	Power loss of battery	kW
U_batt	Voltage output by battery	V
I_batt	Battery current	A
U_batt_oc	Open circuit voltage of batt	V
PW_batt_out	Power output by battery	kW
A/C_Output	Output signals of A/C(eight vectors)	--

Table. 3 Input and Output of A/C system

	Parameter	Description	Unit
Input	Delta m_ar	Air inlet quality of blower	kg/s
	T_esp	Setting temperature evaporator	degC
	T_am	Ambient temperature	degC
Output	T_ev	Evaporator wall temperature of the A/C system	℃
	T_ai	Inlet air temperature of the cabin	℃
	T_ca	Average temperature of the cabin air	℃
	T_cs	Temperature of the cabin shell	℃
	T_ci	Temperature of the cabin interior	℃
	P_c	Power of the compressor	kW

P_b	Power of the blower	kW
E_t	Power consumption of the thermal system	kW

3.1.3. Traffic scenario

There are three parts in the block of the Traffic Scenario, including the preceding vehicle information (V2V), the Sensor information, and the Traffic light information (V2I), as is shown in Fig. 6.

It should be noted that the five traffic scenarios possess different characteristics and a data structure named *TrafficSceneInfo* is summarized in *TrafficData.mat* with items of *AverageSpeed*(in km/h), *TravelTime*(in second), *Distance*(in km) and *TrafficlightNum* for each scenario. Most importantly the algorithm supplied by challenger will be tested in all the five scenarios so please make sure the universality of algorithm.

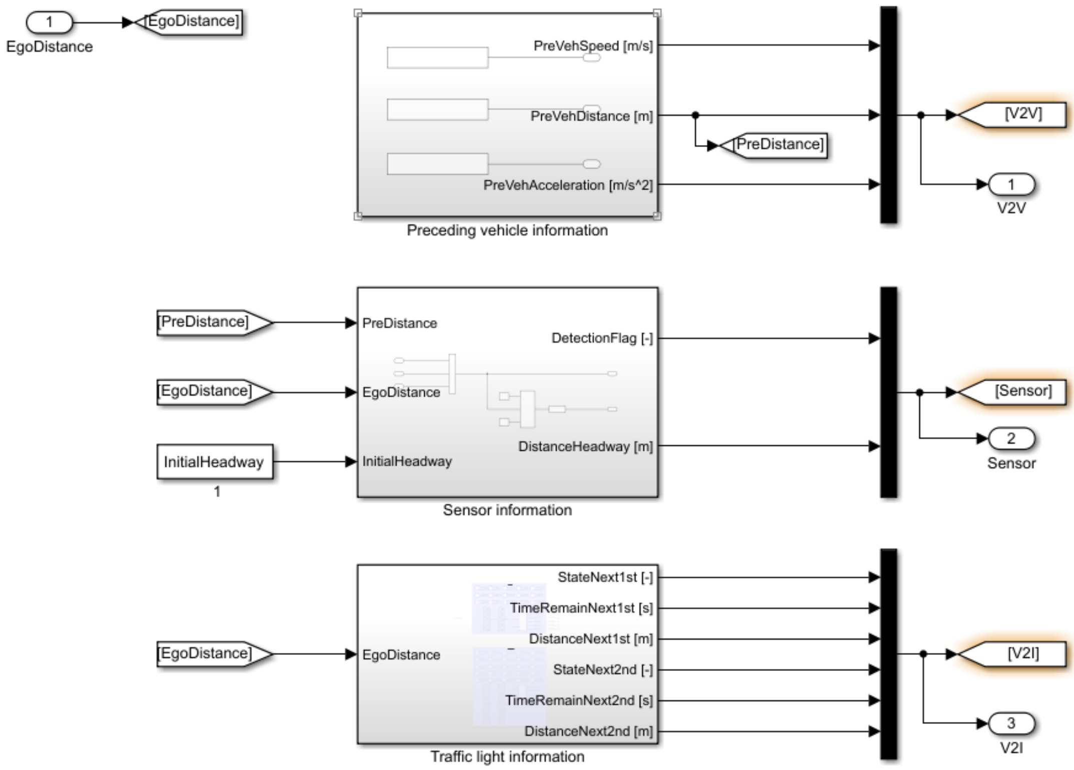


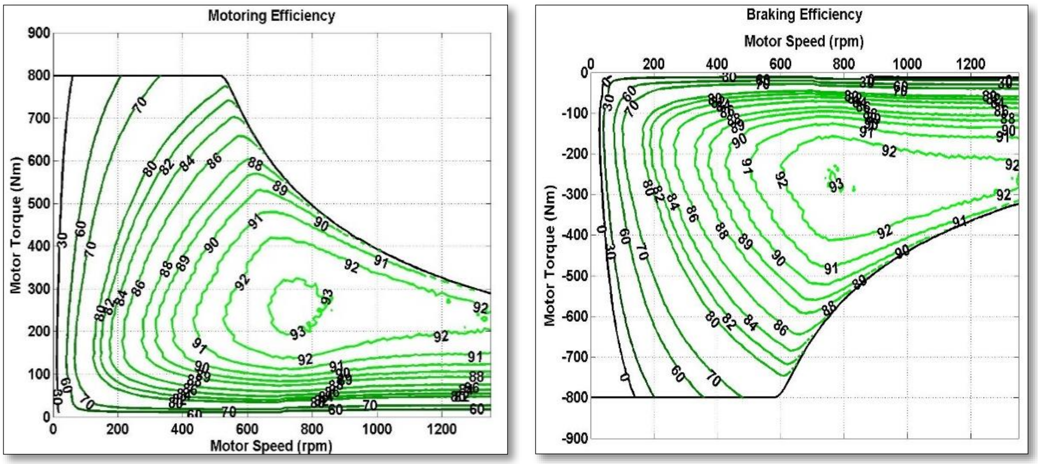
Figure 6: The structure in the block of traffic scenario.

3.2. Component Model and Physical Parameter

In this subsection, the detail models of powertrain and battery, and physical parameter of ego vehicle sensor and V2X are briefly explained, respectively.

3.2.1. Powertrain model

(1) Motors model There are four motors in the vehicle structure, which are MG_{fl}, MG_{fr}, MG_{rl} and MG_{rr}, the subscript denotes the position of the motors mounted. The electric power of motors *PW_motor_mec* are related to *Torque_motor* and *N_motor*. The drive motor modeling is represented as efficiency maps, shown in Fig. 7 (a) and (b). The limitation of speed and torque for motors are also forced. Similarly, the maximum and minimum torques of motor and generator are dependent on the speed.



(a) Motoring Efficiency (b) Braking Efficiency

Figure 7: The maps of efficiencies of motors

For more information, please see the simulator package. Actually, the power loss is given in the simulator and the relationship between the power loss and efficiencies of the generator and motor can be described as follows:

$$\begin{cases} PW\_motor\_mec = N\_motor \times Torque\_motor \\ PW\_motor\_elec = PW\_motor\_mec \times \eta^{k} \\ PW\_motor\_loss = \left| PW\_motor\_elec - PW\_motor\_mec \right| \end{cases} \tag{1}$$

$$if\ \ Torque\_motor < 0,\ k = 1;\ else\ k = -1;$$

(2) Battery model Inner signals of the battery, including battery current, battery voltage and open circuit voltage, are available in the simulator. The model is built based on internal resistance while the detail information is not presented. Based on these real-time signals, the challenger can build the SOC model of battery by yourselves.

3.2.2. A/C system model

As shown in Fig. 8, the cabin air is cooled by the HVAC system through the blower and the evaporator to dissipate the heat transfer into the ambient. In addition, the evaporator is a key part of the HVAC system, as shown in Fig. 8. The actuators in the A/C system including the compressor, the condenser, and the thermal expansion valve, etc., are coordinated to maintain the evaporator wall temperature (T_{ev}) within the desired and safe range. Actually, there exists a low-level Proportional-plus-Integral (PI) controller which take the command from the controller designed by challengers and regulate the behaviors of the physical system via adjusting the electric compressor speed for tracking the evaporator wall temperature set-point (T_{esp}). Furthermore, the inlet air temperature (T_{ai}) of cabin is provided by the blower airflow and evaporator wall temperature.

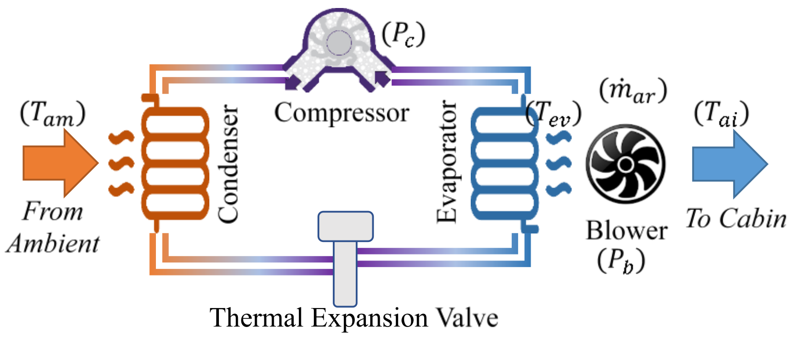


Figure 8. Schematic of the HVAC system

In the cabin space, there are many variables that influence the average temperature of the cabin air (T_{ca}) such as the cabin shell temperature (T_{cs}), cabin interior (e.g., seats and panels) temperature (T_{ci}), the inlet air temperature and the blower airflow rate ($\dot{m}_{ar}$). These variables are required for challengers to capture the cabin temperature dynamic and saturate the comfort of the passengers.

From the power consumption perspective, in addition to blower, the compressor is assumed to be the most significant auxiliary load in the automotive A/C system for thermal management. A special characteristic of the A/C system is the sensitivity of its efficiency to the vehicle speed. As the effective ram air speed through the condenser increases as vehicle speed increases, and then condenser dissipates the heat to the ambient faster, leading to higher efficiency of the A/C system. The vehicle speed sensitivity of the A/C system means the compressor consumes less energy while providing the same cooling power to the cabin when the vehicle speed increases.

For the goal of controller diversity, this benchmark does not provide any detail expression of the A/C system. However, all about information is available in the simulator, where the challengers can obtain it and build the evaporator temperature and power consumption model by yourselves.

3.3. V2X

In the real-world traffic scenario, various traffic information can be obtained, including the preceding vehicle information (V2V), the sensor information, the road slope information (GPS) and the traffic light information (V2I), which will be introduced in the following subsections. All the information in this benchmark that the ego vehicle can obtain is listed in Table. 3.

Table 3: V2X information

Category	Variable	Description	Unit
V2V	PreVehAcceleration	Acceleration of preceding vehicle	m/s^2
	PreVehDistance	Distance of preceding vehicle	m
	PreVehSpeed	Speed of preceding vehicle	m/s
Sensor	DetectionFlag	Sensor detection flag.	--
	DistanceHeadway	Distance headway	m
GPS	RouteSlope	Slope of road	--
V2I	StateNext1st	Phase of 1st next traffic light	--
	TimeRemainNext1st	Remaining time of 1st next traffic light	s
	DistanceNext1st	Distance to the 1st next traffic light	m
	StateNext2nd	Phase of 2nd next traffic light	--
	TimeRemainNext2nd	Remaining time of 2nd next traffic light	s
	DistanceNext2nd	distance to the 2nd next traffic light	m

3.3.1. The preceding vehicle information (V2V)

In this benchmark, only the preceding vehicle is considered for the traffic scene, and the vehicle can obtain the information of the preceding vehicle through V2V communication, including the real-time position, speed and acceleration information of the preceding vehicle. The preceding vehicle information on road 1-5 is shown in Fig 9-13.

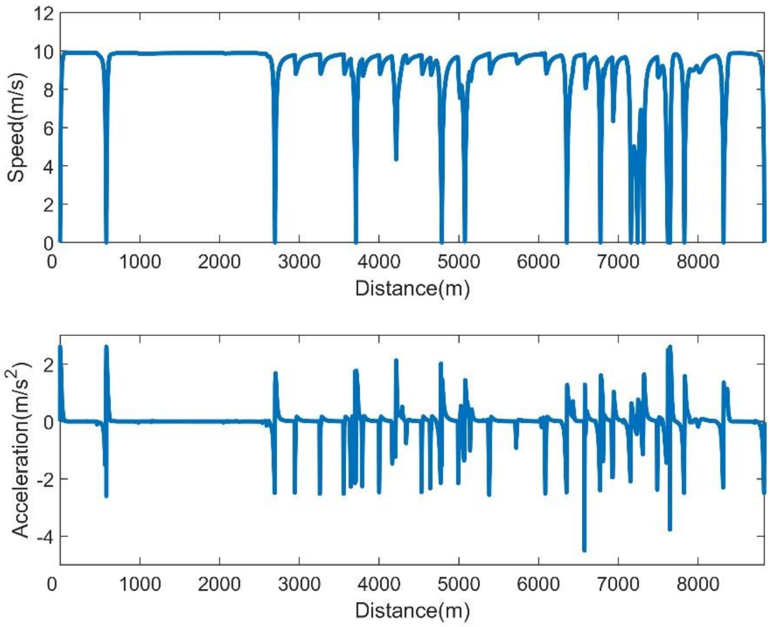


Figure 9: The preceding vehicle information on Road 1

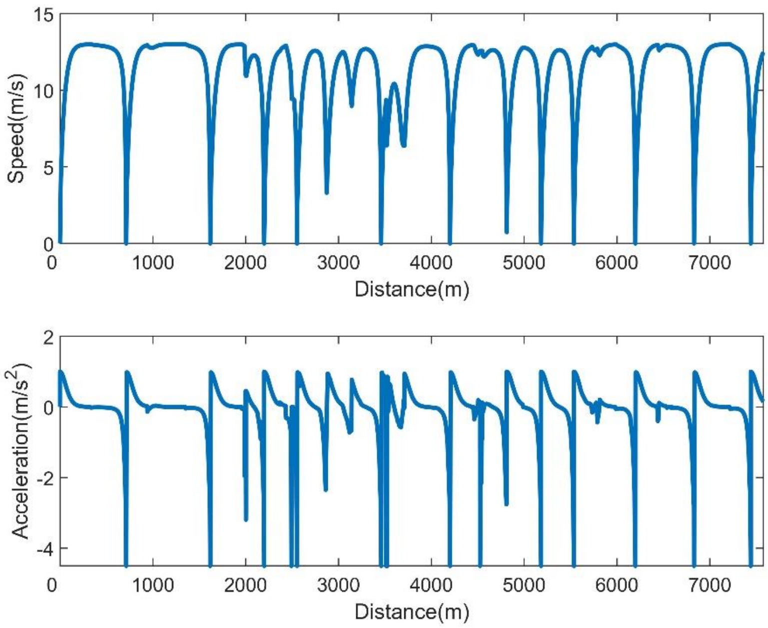


Figure 10: The preceding vehicle information on Road 2

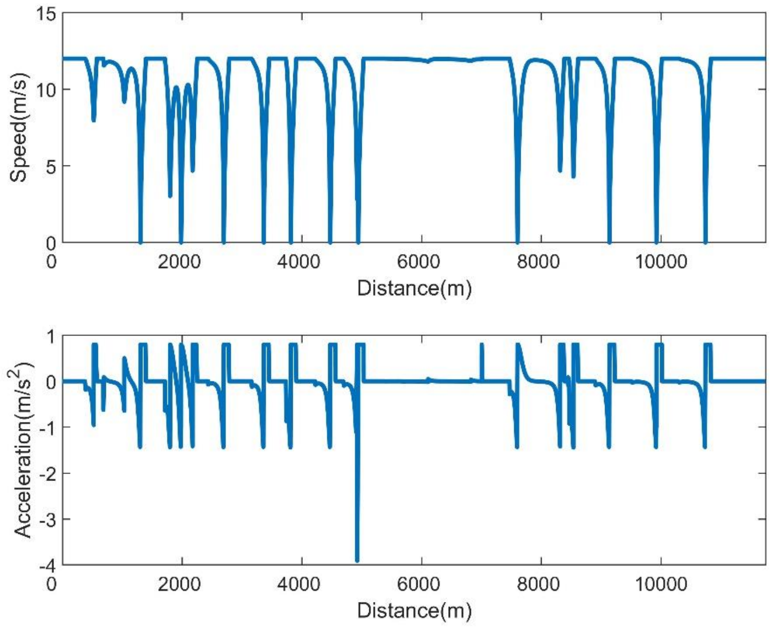


Figure 11: The preceding vehicle information on Road 3

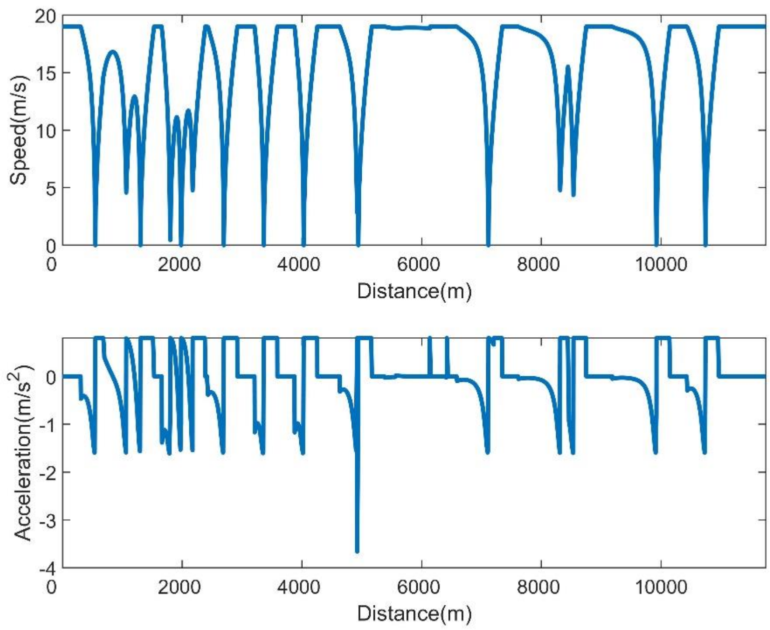


Figure 12: The preceding vehicle information on Road 4

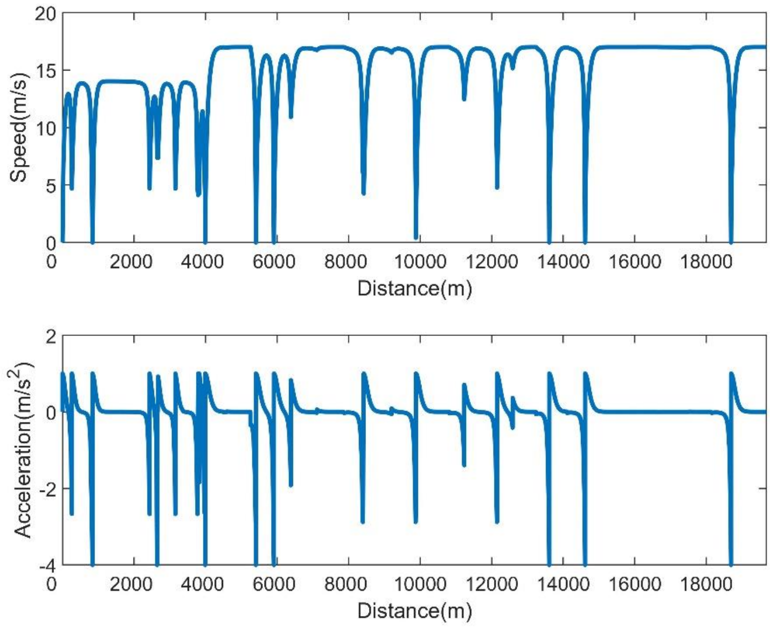


Figure 13: The preceding vehicle information on Road 5

3.3.2. The sensor information

The vehicle sensor can detect the headway distance between the ego vehicle and the preceding vehicle, assuming the detection range of the sensor is 0-200 m.

3.3.3. The road slope information (GPS)

It is assumed that the road in this benchmark is straight without any turns. The ego vehicle obtains road slope information through GPS. In this benchmark, we provide four roads. And their slope information is shown in Fig 14-18

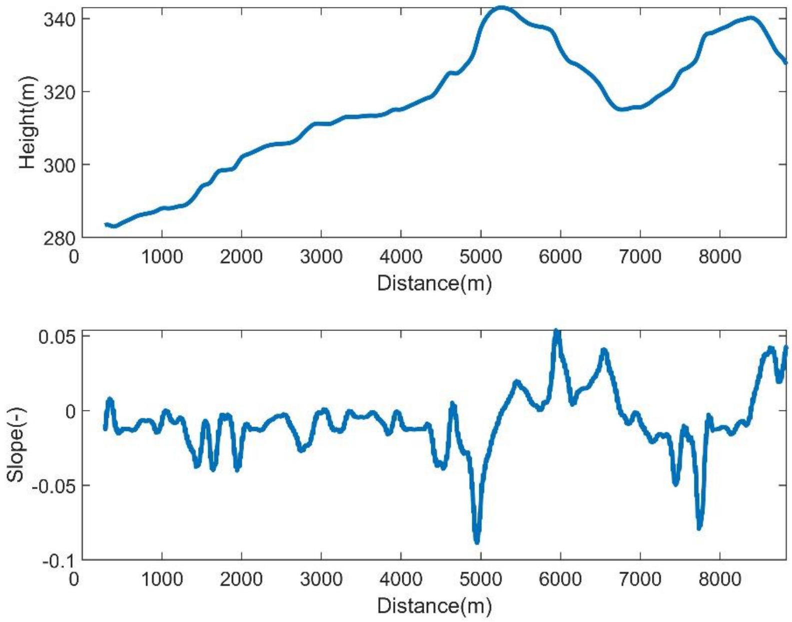


Figure 14: Height and slope of road 1

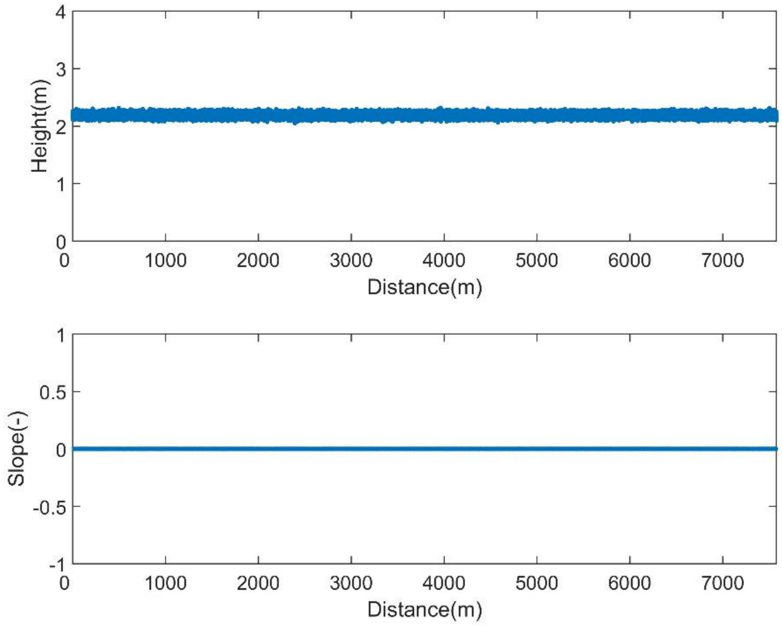


Figure 15: Height and slope of road 2

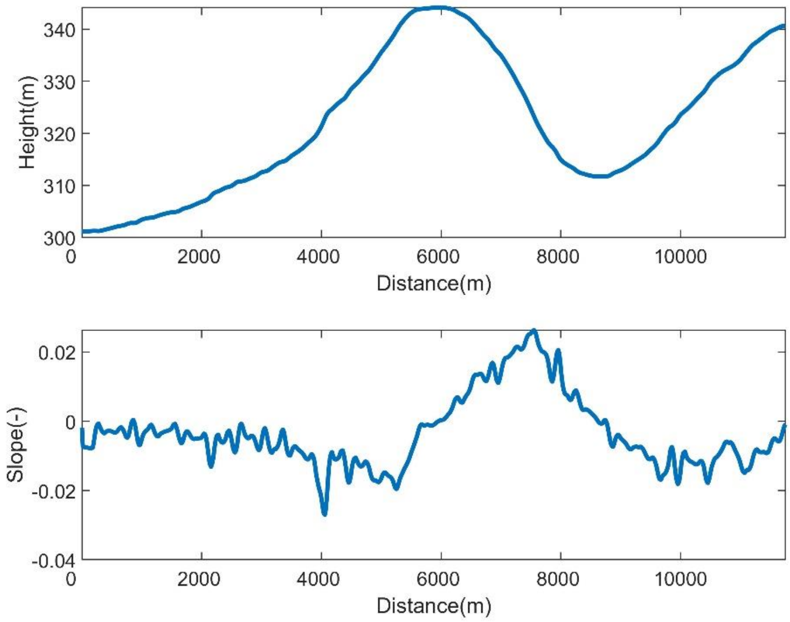


Figure 16: Height and slope of road 3

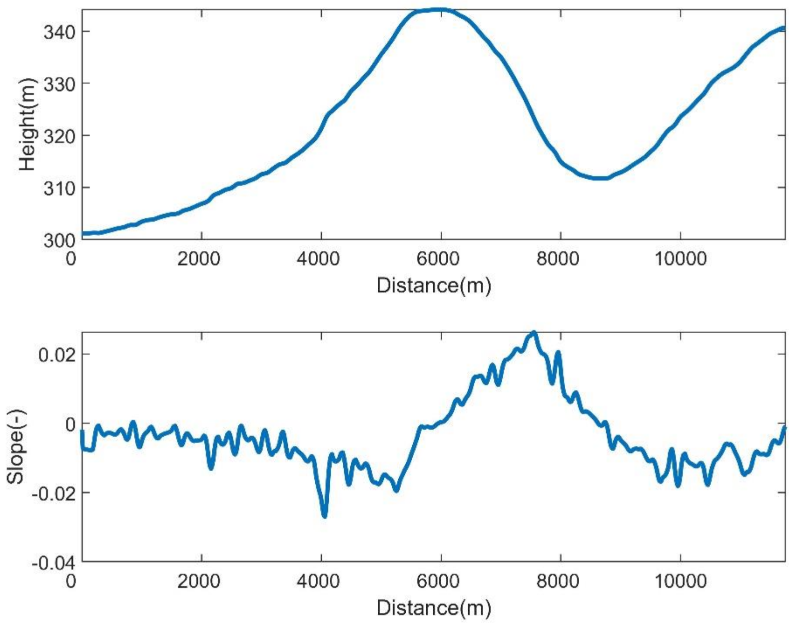


Figure 17: Height and slope of road 4

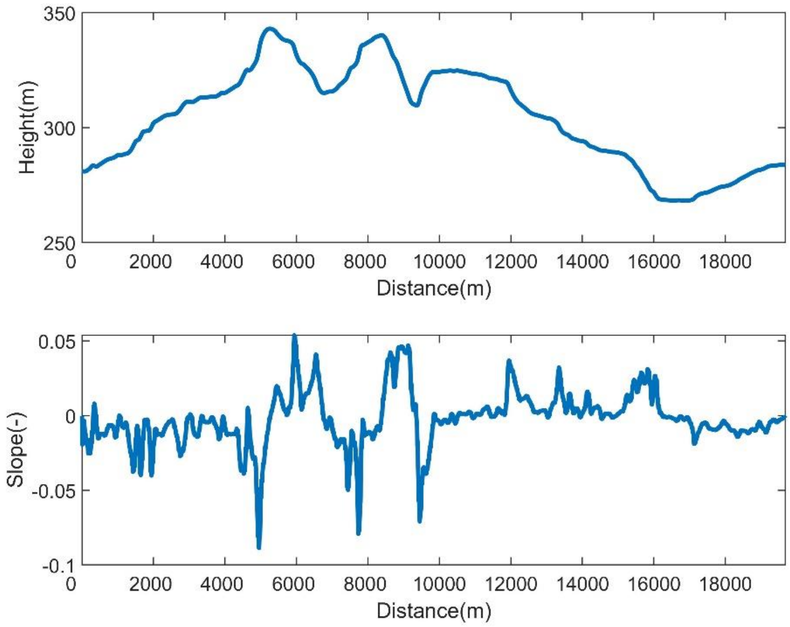


Figure 18: Height and slope of road 5

3.3.4. The traffic light information (V2I)

In this benchmark, we provide five roads. Each road has a certain number of intersections. There is a traffic light at each intersection. The positions of the traffic lights are listed in Table 4-8. And the Phase information of all traffic lights is provided in the simulator.

Table 4: The positions of intersections in road 1

Intersection	Position (m)	Intersection	Position (m)
1	581	9	5539
2	794	10	6058
3	1266	11	6433
4	2718	12	6809
5	3404	13	7348
6	3718	14	7867
7	4307	15	8374
8	5136		

Table 5: The positions of intersections in road 2

Intersection	Position (m)	Intersection	Position (m)
1	161	12	3467
2	261	13	4216
3	721	14	4358
4	853	15	5180
5	1626	16	5536
6	1928	17	5845
7	2200	18	6205
8	2524	19	6493
9	2561	20	6845
10	2893	21	7442
11	3150		

Table 6: The positions of intersections in road 3

Intersection	Position (m)	Intersection	Position (m)
1	311	14	3818
2	436	15	4032
3	549	16	4475
4	772	17	4619
5	1074	18	4943
6	1306	19	6370
7	1606	20	7118
8	1802	21	7604
9	1983	22	9141
10	2697	23	9925
11	3027	24	10270
12	3365	25	10744
13	3647		

Table 7: The positions of intersections in road 4

Intersection	Position (m)	Intersection	Position (m)
1	311	14	3818
2	436	15	4032
3	549	16	4475
4	772	17	4619
5	1074	18	4943
6	1306	19	6370
7	1606	20	7118
8	1802	21	7604
9	1983	22	9140
10	2697	23	9925
11	3027	24	10270
12	3365	25	10744
13	3647		

Table 8: The positions of intersections in road 5

Intersection	Position (m)	Intersection	Position (m)
1	3984	9	9881
2	4380	10	10418
3	4481	11	11270
4	5407	12	12671
5	5911	13	13611
6	6410	14	14613
7	7415	15	15000
8	9412	16	18695

4 Challenging and Evaluating

4.1 Challenging

The challengers can use the signals from block of Traffic Scenario and the output signals from the block of Plant Model. It is noted that the provided signals may be surplus and the challengers can discretionarily select some of them for your controller design. But the controller should be set in the Controller block. The other blocks, such as Traffic Scenario, Plant Model and Index Performance are not allowed to make any modification.

The task of the benchmark is to design a controller that achieving the minimization of electricity consumption. The real-time dynamic information of powertrain, battery HVAC system, cabin and vehicle are available to the controller. Meanwhile, the real-time traffic scenario information, including ego vehicle sensor, GPS, V2I and V2V, are also provided to the controller. The challengers can be selective to use above real-time information. Moreover, the safety constraints, including vehicle speed and distance headway between ego vehicle and preceding vehicle should be satisfied. The physical constraints of powertrain, battery, cabin and vehicle should be satisfied. Additionally, the stop constraint when facing a red traffic light at the intersection should be considered.

In the following, the above four tasks will be introduced in detail.

4.1.1 Electricity consumption

The main goal is to improve the energy efficiency of EVs in the connected environment with hot weather. The goal can be seen as the minimization of electricity consumption of the battery, which consists of the power consumer of the powertrain system and the power consumer of the HVAC system. However, overtaking behavior is not allowed in the traffic scenario.

4.1.2 Physical constraints

The physical limitations of the powertrain, the battery, the HVAC system that the vehicle has to follow are written as follows:

$$\begin{cases} TQ_{e,\min} \le TQ_e \le TQ_{e,\max} \\ \omega_{e,\min} \le \omega_e \le \omega_{e,\max} \\ P_{batt,\min} \le P_{batt} \le P_{batt,\max} \\ SOC_{\min} \le SOC \le SOC_{\max} \\ \dot{m}_{ar,\min} \le \dot{m}_{ar} \le \dot{m}_{ar,\max} \\ T_{ev,\min} \le T_{ev} \le T_{ev,\max} \end{cases} \quad (2)$$

where the minimum and maximum torque of motor are also dependent on corresponding speeds. And the detail values of other parameters are listed in Table. 6.

Table 9: The values of minimum and maximum powertrain system parameters

Parameter	Value [Unit]	Parameter	Value [Unit]
Torque_motor_min	10 [Nm]	Torque_motor_max	800 [Nm]
N_motor_min	50 [rpm]	N_motor_max	1350 [Nm]
PW_batt_min	-339 [kW]	PW_batt_max	339 [kW]
SOC_min	4.8%	SOC_max	99.2%
$\dot{m}_{ar,min}$	0 [kg/s]	$\dot{m}_{ar,max}$	0.15 [kg/s]
$T_{ev,min}$	2 [°C]	$T_{ev,max}$	24 [°C]

The initial conditions of powertrain, vehicle, battery and cabin are also determined:

$$\begin{cases} x(t_0) = 0 \\ v(t_0) = 0 \\ \omega_e(t_0) = \omega_{e,0} \\ SOC(t_0) \le SOC_0 \\ T_{ev}(t_0) = T_{ev,0} \\ T_{ca}(t_0) = T_{ca,0} \end{cases} \quad (3)$$

4.1.3 Boundary constraints

(1) The longitudinal headway distances between ego vehicle and surrounding vehicles for driving safety should be considered, which is shown as follows:

$$d_h \ge s_0 + vt_d \quad (4)$$

where s_0 is the minimum allowed distance headway and t_d denotes the driver reaction time.

(2) The average temperature of the cabin, $T_{ca,avg}$, is defined by

$$T_{ca,avg} = \frac{\sum_{k=0}^{Travel_i} T_{ca,k}}{Travel_i} \quad (5)$$

where $Travel_i$ is the total travel time in the i-th testing traffic scenario, $T_{ca,k}$ is the cabin air temperature at the time instant k. The average temperature of the cabin directly affects the passenger's thermal comfort which should be constrained as follows:

$$T_{ca,avg} \le T_{ca,des} + \varepsilon_{Tca} \quad (6)$$

where $T_{ca,des}$ is the desired temperature of the cabin air, which is set as 23.5℃, ε_{Tca} is the temperature margin for the controller, which is set as 1.5℃.

(3) When the traffic light is red, the vehicle has to stop before 25 [m] to the central of intersection, which is the end of previous link and the start of the new link. If the ego vehicle does not stop before the stop line when facing with the red light, a punishment time will be added to the actual travel time.

4.2 Evaluating

The materials for submitting benchmarking results should be delivered to us in a single package and the file format should be as zip or rar. Following actions should be completed in the package:

- The version of MATLAB for controller must be 2020b.
- The main file of the designed controller must be as a module named FirstAuthorName _Controller and saved as FirstAuthor _Controller.slx.
- The necessary pre-computations parameters for controller should be saved in the FirstAuthor_Initial parameters.m.
- The success of submission is only certified based on a letter in reply from us.

When the final controller packages of challengers are received to us, the performance of controllers will be evaluated in other 4 random environment conditions, but the road and slope are same as the sample data that have been provided in the public simulator. Specifically, the traffic densities on the links and initial phase and timing of traffic lights in the 4 random traffic scenarios are different from these in the sample data. Besides, the ambient temperature is also different from the value provided in the public simulator. The championship evaluating process will be conducted through the following items.

4.2.1 Disqualification

The challenger will be disqualified if one of the following rules is broken by the challenger:

- $v_i > 80\ [km/h]$: Ego vehicle speed is higher than the speed limitation on the road.
- $d_{h,i} \le 0\ [m]$: the distance between ego vehicle and preceding vehicle is not higher than 0, that is a case of crush accident.
- $red_i > 1\ [-]$: Ego vehicle runs through intersection during the red light is more than 1 time.
- $Tr_i > Tr_{pre,i} + 60 + 30\ [\text{sec}]$: The travel time of ego vehicle is higher than the travel time of preceding vehicle plus additional 90 [sec].
- $T_{sim} \le 3600\ [\text{sec}]$: The actual simulation time after results obtained must be within 1 hour.

4.2.2 Scoring

The total electricity consumptions in the 5 testing traffic scenarios are used to obtain the score for each challenger. The fuel consumption and the arriving time will be evaluated individually with the following methods:

(1) Total electricity consumption

$$E = \sum_{i=1}^{4} \left\{ E_e + E_t + E_p \right\} \tag{7}$$

where i indicates the index of testing scenario for challengers, the first term is the total electricity consumption of the powertrain system.

$$E_e = \int_0^{Travel_i} PW_{batt,out} \Delta t \tag{8}$$

In (7), the second term is the total electricity consumption of the A/C system.

$$E_t = \int_0^{Travel_i} \left(P_c + P_b \right) \Delta t \tag{9}$$

where P_c and P_b are the total electricity power of the compressor and the blower, respectively. The third term E_p is penalty for violation of thermal comfort.

$$E_p = \begin{cases} \int_0^{Travel_i} \gamma_p \left(T_{ca,avg} - T_{ca,des} - \varepsilon_{Tca} \right) \Delta t & T_{ca,avg} > T_{ca,des} + \varepsilon_{Tca} \\ 0 & T_{ca,avg} \le T_{ca,des} + \varepsilon_{Tca} \end{cases} \tag{10}$$

where γ_p is the penalty factor. When $T_{ca,avg} > T_{ca,des} + \varepsilon_{Tca}$, there is a violation of cabin air temperature. To challenge the fuel-saving effect, $T_{ca,avg} - T_{ca,des} - \varepsilon_{Tca}$ should be transformed to electricity consumption by using the equivalent factor $\gamma_p > 0$. Based on the energy consumption of the thermal system, the equivalent factor is set as 180W/(°C·s).

(2) Travel time

$$Alltravel_i = Travel_i + Tred_i \tag{11}$$

where the second term is penalty for red light crossing, which means each time of red-light crossing would plus additional 60 [sec].

With satisfaction of the physical and boundary constraints and removing the disqualified challengers, the championship goes to the one challenger with least total electricity consumption in the rest challengers.

5 Challenge Process

5.1 How to participate

(1) Challengers need to download the registration form from the official website, fill it up and send it back to the designated email address for review according to the request on *http://www.ascl.jlu.edu.cn/vci/cvci2023/Benchmark.htm.*

(2) After the review, the organizer will send the model package (electric vehicle model, traffic model and related data) to challengers.

(3) After receiving the model package, challengers need to develop relevant algorithms and programs for the proposed problems. The program code should adapt for the Matlab version specified by the organizer.

(4) Challengers should submit the specification of the algorithm they designed before the deadline specified by the official website of CVCI2023, describing in detail the optimal control algorithm used. The specification can be written as a full paper to participate in the submission of the CVCI2023 paper, or it can only be used as a position

paper to participate in the challenge.

(5) Challengers need to submit the algorithm program due by the deadline specified in the official website. The organizer will run the submitted code on the simulator and evaluate the simulation data. Challengers' solutions are ranked and awarded according to the comprehensive energy consumption according to the submitted programs. Note that, in order to ensure fairness, the traffic scenarios for testing will not be announced.

5.2 Awards

(1) There will be one gold, two silvers and several bronze prizes for the challenge.

(2) Challengers need to register and participate in the CVCI2023 conference, and share their control schemes and communicate on the Special Session of the challenge. After the exchange, the organizer will announce the list of winners.