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Influence and Optimization of Packet Loss on the Internet-Based Geographically Distributed Test Platform for Fuel Cell Electric Vehicle Powertrain Systems

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ABSTRACT In view of recent developments in fuel cell electric vehicle powertrain systems, Internet-based geographically distributed test platforms for fuel cell electric vehicle powertrain systems become a development and validation trend. Due to the involvement of remote connection and the Internet, simulation with connected models can suffer great uncertainty because of packet loss. Such a test platform, including packet loss characteristics, was built using MATLAB/Simulink for use in this paper. The simulation analysis results show that packet loss affects the stability of the whole test system. The impact on vehicle speed is mainly concentrated in the later stage of simulation. Aiming at reducing the effect of packet loss caused by Internet, a robust model predictive compensator was designed. Under this compensator, the stability of the system is greatly improved compared to the system without a compensator.

INDEX TERMS Fuel cell electric vehicle, powertrain system, Internet-based distributed test platform, packet loss, robust model prediction compensator.

I. INTRODUCTION

With the continuous development of computers, as well as network and communication technology, Internet technology has become an effective solution for meager linkage in the development process. With the development of ‘‘Industry 4.0’’ and ‘‘Internet+,’’ distributed test systems based on wireless network Internet have become a hot topic in research and industrial fields [1], [2]. They have significant advantages in completing complex, remote, and wide-ranging measurement and control tasks. However, the quality of the operation depends on the quality of the data transmission. Therefore, the quality of the network directly affects the performance of test platforms.

In recent years, several research institutions and companies have studied Internet-distributed test platforms. It is known from the literature that the threshold for instability depends on the specific configuration of the system and the combined effects of other QoS (quality of service) parameters, namely delay, jitter and packet loss. Packet loss means that data of one or more data packets cannot reach the destination through the network. There are two reasons for packet loss: one is because the transmission channel is shared by multiple nodes in the system, and the network bandwidth is limited, and the number of sensors and actuators that can access data with the controller at a certain time is limited. When the load is large, data collisions, network congestion, and node

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failures often occur, and data collisions and node failures will result in packet loss. The other is that in the real-time control system, the system often discards the data packets that have not arrived at a certain time, and then sends new data to ensure the timely update of the signals and the validity of the sampled data. Schreiber et al. analyzed packet loss and delay in the existing network state [3]. Delay influences the stability of the system. The possibility of application of the distributed test platform is not optimized for stability. Rahmani et al. studied a network-based hardware-in-the-loop simulation control system, thus, a predictive control strategy was carried out, but the authors found no other impact on system stability [4]. Damo et al. developed a TPG (Total Peripherals Group) software for fuel cell software-in-the-loop technology [5]. Their research validated the feasibility of the distributed test system. The software for the platform was developed, the impact of data loss on system stability was not studied or optimized.

Walker et al. studied the data loss problem in remote operation of the Internet in the presence of delay [6]. The results showed that the fidelity of a remote system would not be significantly affected when the packet-loss rate (PLR) was about 3%. Brudnak *et al.* [7] connected the motion-based simulator and hybrid powertrain system with the Internet employing a user diagram protocol (UDP), The PLR remained at a low 0.1%; thus, stability was less affected. In general, a higher PLR leads to a higher risk of instability. Borella et al. analyzed Internet packet loss statistics and found that most of the loss was due to bursts and consecutive losses [8]. As can be seen from the above literature, packet loss would degrade over time, which brought additional instability risks. It also affects the real-time performance of Internet distributed systems.

For optimization of data packet loss, Tang et al. investigated the synthesis approach of output feedback model predictive control (OFMPC) for nonlinear systems over networks where packet loss may occur simultaneously, a new technique for refreshing the estimation error bound, which plays the key role of guaranteeing the recursive feasibility of optimization problem [9]. Based on robust least-square approach, Wu et al carried out a parameter-dependent predictive controller and an iterative algorithm to solve the packet loss and uncertainty optimization problem for a networked robotic visual servoing system [10]. Ju et al. presents a dynamic optimization solution for the data packet-based communication of programmable logic controller (PLC) visual monitoring, and the objective is to improve the communication efficiency between a supervisory computer and field PLCs in consideration of the network communication performance, such as packet loss [11].

Existing research mainly focuses on delays in data transmission of Internet based distributed test systems. The studies focus on data packet loss are not enough to solve stability problem of Internet based distributed test systems. Our research direction for the data packet loss problem is to assess the impact of packet loss. This paper focuses on the optimization of methods to prevent data packet loss.

In general, the Internet based distributed test system is a relatively new technology in the field of modern validation and testing. However, to achieve standardization and marketization of the technology, analysis and optimization issues regarding Internet data packet loss on system stability are necessary. This paper presents a study of the data packet loss problem of distributed FCEV powertrain systems and carries out an analysis on the influence of data packet loss on the stability of the system with an emphasis on system optimization designed to minimize this problem.

II. SYSTEM MODELING

Tongji University in Shanghai, China and Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany jointly developed a distributed test platform for an FCEV powertrain system [12]–[14]. The objective was to remotely connect the distributed platform's developed environment and data transfer capability between two computers—one in China at Tongji University and the other in Germany at KIT. Since we tried to compare the results from different connection settings, the test platform components of each developer were placed on both sides of the virtual or physical model as a configuration requirement. The whole structure of this distributed test platform is shown in Figure 1.

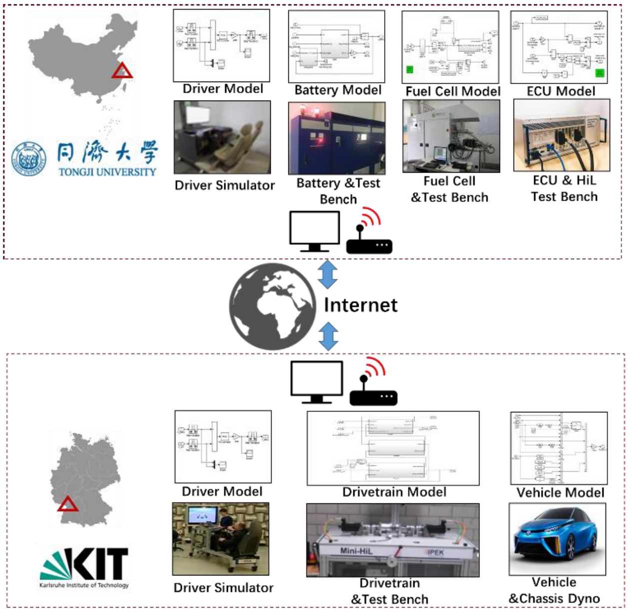

FIGURE 1. Structure of the distributed test platform for FCEV powertrain systems.

According to the structure, the virtual models or hardware on both sides flexibly combined. Aimed at packet loss research, on the Chinese side of the driver model, the electric control unit (ECU), battery and fuel cell models were chosen. While on the German side, the drivetrain and vehicle models were chosen.

The vehicle model parameters are listed in Table 1.

TABLE 1. Vehicle parameters.

Name	Value	Unit
Vehicle weight	1600	kg
Transmission ratio	1	-
Transmission system efficiency	92	%
Tire radius	0.3	m
Rolling resistance coefficient	0.01	-
Air resistance coefficient	0.35	-
Frontal area	2.8	m^2
10 °C sea level air density	1.2	N·s^2·m^{-4}
Rotational mass conversion factor	1.05	-
Drive torque	-	N·m
Vertical speed	-	m/s
Vertical acceleration	-	m/s^2

Proton exchange membrane fuel cells (PEMFC) use hydrogen and oxygen to generate electrical energy through electrochemical reactions [15], [16]. The fuel cell's working mechanism cannot be described by a simple mathematical formula. The fuel cell subsystem's complexity made its dynamic response worse and was adversely affected by the surrounding work environment. A simplified model was established with reference to the models of [17], [18]. Parameter identification and data fitting are common methods to improve the accuracy of the simplified model and make its applicability easier to understand. When the load current changed, due to the charging effect, the fuel cell's bipolar plate surface produced a slowly changing voltage. The parameter values of the fuel cell model are shown in Table 2.

TABLE 2. Fuel cell values.

Name	Value	Unit
Single fuel cell internal resistance	0.0003	Ω
Single fuel cell equivalent resistance	0.0006	Ω
Single fuel cell open circuit voltage	1.037	V
Single fuel cell equivalent capacitor	3	F
Fuel cell rated power	6	kW
Fuel cell peak power	6.5	kW

The battery made up for the lack of dynamic response of the fuel cell and absorbed the energy of the brake [19]–[21]. Here a packaged ternary polymer lithium battery model was used. Battery and fuel cell were connected in parallel, using a power following strategy. In this paper, the analytic model of the battery was used. Battery current and temperature were input, and the output was voltage and state-of-charge (SOC). By stationary state the charging mode of our vehicle was a constant current-constant voltage (CC-CV) cycle. For this battery model, the following assumptions are accepted: the internal resistance of the battery model is constant, that is, the internal resistance value is kept constant during the charging and discharging of the battery, and is also independent of the charge and discharge current; there is no memory effect in the battery. The parameter values of the battery are shown in Table 3.

The electric motor model was a quasi-steady-state model. The electric motor values are shown in Table 4.

TABLE 3. Battery values.

Name	Value	Unit
Maximum current	500	A
Maximum charge current	−45	A
Number of series batteries	100	-
Number of parallel batteries	20	-
Battery cell radius	0.013	m
Battery cell height	0.065	m
Battery cell capacity	2.3 × 3600	Ah·s
C-rate (charge-discharge current/rated capacity)	1	C

TABLE 4. Electric motor values.

Name	Value	Unit
Drive Type	4 In-Wheel Motor	–
In-Wheel Motor Rated/Peak Power	4 × 0.8/4 × 2.5	kW

The FCEV powertrain system mathematical model in the time domain was carried out. While this system was a multi-input, multi-output and nonlinear system, after appropriate simplification it was abstracted into a linear constant control system. Its system space state equation is as follows:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} = \mathbf{Cx} + \mathbf{Du} \end{cases} \tag{1}$$

where state variables $\mathbf{x} = \begin{bmatrix} \Delta U & U_b & I_m \end{bmatrix}^{\mathrm{T}}$, input variables $\mathbf{u} = \begin{bmatrix} I_f & P_{\min} \end{bmatrix}^{\mathrm{T}}$, output variables $\mathbf{y} = \begin{bmatrix} U_{busls} & 0 \end{bmatrix}^{\mathrm{T}}$, and the coefficient matrix are expressed as:

$$\mathbf{A} = \begin{bmatrix} -\dfrac{1}{T_f} & 0 & 0 \\ 0 & 0 & \dfrac{1}{C} \\ 0 & 0 & -\dfrac{1}{T_m} \end{bmatrix}; \quad \mathbf{B} = \begin{bmatrix} \dfrac{K_f}{T_f} & 0 \\ -\dfrac{1}{C} & 0 \\ 0 & \dfrac{K_m}{T_m} \end{bmatrix};$$

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & R \\ 0 & 0 & 0 \end{bmatrix}; \quad \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

III. ANALYSIS OF THE IMPACT OF PACKET LOSS

A. NETWORK STATUS TEST

In order to accurately understand the network status between China and Germany, the network transmission status between Tongji and KIT was tested with the Collet Ping tool. The test results are shown in the Table 5.

According to test results, the round-trip time of the data packet varied due to the network load and was concentrated in 360 ms most of the time. The data PLR was below 5% in most cases.

B. PACKET LOSS MODEL BASED ON MARKOV RANDOM PROCESS

In order to build a packet loss model, the packet loss process should be described. The random packet loss process is described as follows: Assume that the zero-order

TABLE 5. **Sino-german network status test results.**

Measuring date	Measuring period	Number of packets	Number of lost packets	Packet loss rate (%)	Min RTT (ms)	Average value(ms)	Variance
2017.3.14	3-4pm	2030	42	2	369	389.576	36.48
	9-10pm	2157	94	4	368	401.242	66.19
2017.3.15	3-4pm	2201	172	7	361	389.893	46.23
	9-10pm	2080	26	1	369	388.689	35.61
2017.3.16	3-4pm	2075	115	5	369	415.213	69.57
	9-10m	2028	68	3	370	407.083	45.51
2017.3.17	0-1am	938	68	7	267	353.724	73.03
	3-4pm	2281	21	0	368	392.6814	32.57
	9-10pm	2158	98	4	368	401.104	54.39
2017.3.18	6-7am	578	17	2	186	224.187	37.80
	8-9am	1846	41	2	194	270.600	39.61
	2-4pm	2989	49	2	335	355.277	35.63
2017.3.19	6-7am	2107	7	0	204	246.195	36.13
	8-9am	991	4	0	206	280.689	27.48
	2-4pm	3496	16	0	335	346.655	19.90
2017.3.20	3-4pm	2092	187	8	271	356.504	43.39
	9-10pm	2292	48	2	334	369.458	58.36
2017.3.21	0-1am	2134	314	14	204	308.031	43.64

keeper successfully received the data packet at the time i_k $(k = 1, 2, \cdots)$, and $\Theta = \{i_1, i_2, \cdots\}$ is the sub-sequence of $\{1, 2, 3, \cdots\}$, here i_k indicated that the data packet arriving at the zero-order keeper for the k time corresponds to the data of the sampler time. The number of consecutive packet losses between two successful transmissions can be calculated as:

$$\eta(i_k) = i_{k+1} - i_k, i_k \epsilon \Theta \tag{2}$$

Maximum packet loss upper bound is

$$s = \max_{i_k \in \Theta} \{\eta\,(i_k)\} = \max_{i_k \in \Theta} \{i_{k+1} - i_k\} \tag{3}$$

If $\forall k \in Z_+, i_{k+1} - i_k = 1$, no packet loss happens. Let $i_0 = 0$ then

$$\bigcup_{k=0}^{\infty} [i_k, i_{k+1}) = [0, \infty) \tag{4}$$

The packet loss process is defined as Eq. (2) and met $\eta(i_k) \in S = \{1, 2, \cdots s\}$. If any data packet loss was random and it took value in Θ, this data packet loss process was a Markov process, which is a discrete-time homogeneous Markov chain in probability space, and its transition probability matrix is

$$\prod = (p_{ij}) \in R^{s \times s} \tag{5}$$

For all $i, j \in S$

$$p_{ij} = P\{\eta(i_{k+1}) = j\,|\eta(i_k = i)\} \geq 0 \tag{6}$$

The Markov packet loss process was seen as a special case of arbitrary packet loss.

Network packet loss is a random event. A random variable X is set to represent the packet event.

$$\begin{cases} X = 0 & \text{“no packet lost ”} \\ X = 1 & \text{“a packet lost ”} \end{cases} \tag{7}$$

P represents a probability from 0 state to 1 state, denoted as P_{01}, Q represents a probability from 1 state to 0 state.

$$P(X = 1\,|X = 0) = \frac{\text{The number of packet loss events}}{\text{The number of 0 state appears}} \tag{8}$$

$$P(X = 0\,|X = 1) = \frac{\text{The number of packet loss events}}{\text{The number of 1 state appears}} \tag{9}$$

Here $1 - P$ represents P_{00}, i.e. $P\,(X = 0|X = 0)$, $1 - Q$ represents P_{11}, i.e. $P\,(X = 1|X = 1)$. The relationship of these events is shown in Figure 2.

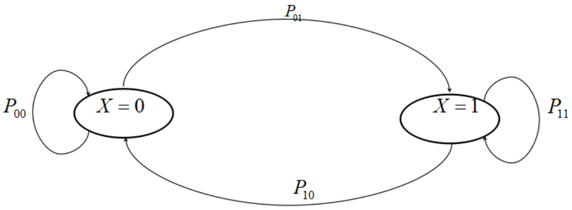

FIGURE 2. **Markov loss probability function.**

Let P_1 represent total packet loss rate (ulp). P_{11} is recorded as clp. P_0 represents the total average no packet loss rate. The calculation of each is given as:

$$P_0 = \frac{\frac{1}{P}}{\frac{1}{P} + \frac{1}{Q}} - \frac{Q}{P + Q} \tag{10}$$

$$P_1 = 1 - P_0 = \frac{P}{P + Q} \tag{11}$$

$$Q = 1 - clp \tag{12}$$

$$P = \frac{ulp(1 - clp)}{1 - ulp} \tag{13}$$

The probability geometric distribution of continuous packet loss length K is

$$\begin{aligned} P\,(Y = K) &= P(X = 1\,|X = 1\,)^{k-1} P(X = 0\,|X = 1\,) \\ &= clp^{k-1}(1 - clp) \\ &= (1 - Q)^{k-1} Q \end{aligned} \tag{14}$$

The mathematical expectation of Y is

$$E(Y)=\sum_{k=0}^{\infty}kP(Y=k)=\sum_{k=0}^{\infty}k\cdot clp^{k-1}(1-clp)=\frac{1}{Q} \tag{15}$$

Based on the Markov random process and the network quality test between the Chinese and German sides, the continuous packet loss length and packet loss times are shown in Table 6.

TABLE 6. **Continuous packet loss length.**

Continuous packet loss length	0	1	2	3	4
Packet loss times	1988	19	5	3	1

Note: Select the 2017/3/14 (3 pm–4 pm) time period.

Therefore, the probability of packet loss can be calculated as shown in Table 7.

As shown in Table 7, the PLR of the test period was 0.021, and the correlation between packet loss events was not strong. The probability of occurrence for each packet loss event was a random event. Continuous packet loss length was 1.499, indicating that packet loss tended to single packet loss.

TABLE 7. **Packet loss parameter value.**

Parameter	ulp	clp	P	Q	E(Y)
Value	0.021	0.333	0.014	0.667	1.499

Note: Select the 2017/3/14 (3 pm–4 pm) time period.

C. POWERTRAIN SYSTEM SIMULATION WITH PACKET LOSS

According to the actual measurement of network status results between China and Germany, especially the packet loss status, the performance of the distributed test platform was analyzed. As shown in Figures 3-4, the simulation results clearly reflect the impact of data packet loss on output speed.

The trends show that the impact of data packet loss on vehicle speed was mainly concentrated in the high speed and ultra-high speed range. When the data PLR exceeded 5%, the output speed exceeded the error tolerance range. Output speed fluctuations occurred at both normal speed and high speed moments. In response to this phenomenon, it was necessary to optimize the impact due to data packet loss.

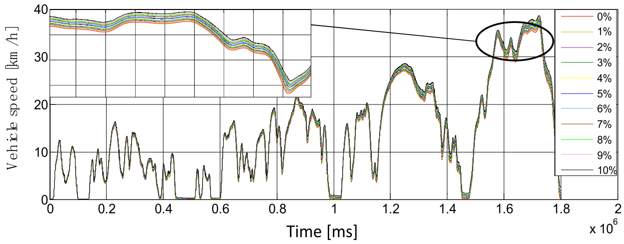

FIGURE 3. **Trends of vehicle speed over time at different data packet loss rates.**

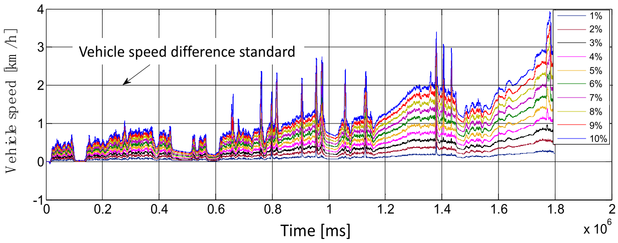

FIGURE 4. **Trend of vehicle speed at different data packet loss rates.**

IV. OPTIMIZATION APPROACH WITH ROBUST MODEL PREDICTIVE COMPENSATOR (RMPC)

A. DESIGN OF COMPENSATOR

In order to facilitate the study of the impact of data packet loss on the stability of the FCEV powertrain system's distributed test platform, the platform was simplified to a network control system based on an RMPC (robust model predictive control), where $\mathbf{x}$ and $\mathbf{u}$ were the input and output of the actuator, and $\mathbf{x}_c$, $\mathbf{u}_c$ were the input and output of the controller. Since the controller and the actuator were connected through the Internet, in the process of data packet transmission, data packet loss occurred due to network congestion. The system state equation is

$$\begin{cases}\mathbf{x}(k+1)=\mathbf{A}(\delta(k))\,\mathbf{x}(k)+\mathbf{Bu}(k)\\ \mathbf{y}(k)=\mathbf{Cx}(k)\end{cases} \tag{16}$$

Here $\delta(k)$ is the system uncertainty parameter

$$\delta(k)\in\Delta\triangleq\left\{\delta=\left[\delta_1,\cdots,\delta_g\right]^T:\delta_j\in\left[a_j,b_j\right]\right\} \tag{17}$$

The system uncertainty matrix satisfies the following form

$$\mathbf{A}(\delta(k))=\sum_{j=1}^{L}\lambda_j(\delta(k))\,\mathbf{A}_j \tag{18}$$

Here, $\sum_{j=1}^{L}\lambda_j(\delta(k)) = 1, \lambda_j(\delta(k)) \geq 0, j = 1,\cdots,L$ which requires that we set the following to express data loss:

$$\mathbf{x}_c=\begin{cases}\mathbf{x}(k) & \text{no data loss}\\ \mathbf{x}(k-1) & \text{data loss}\end{cases} \tag{19}$$

For data packet loss in the system, two random sequences $\{\alpha_1(k)\}$ and $\{\alpha_2(k)\}$ were introduced to describe the data packet loss. $\{\alpha_1(k)\}$ was the description of packet loss between actuator and controller, $\{\alpha_2(k)\}$ was the description of packet loss between controller and actuator. Therefore,

$$\mathbf{x}_c(k)=\alpha_1(k)\,\mathbf{x}(k),\ \mathbf{u}(k)=\alpha_2(k)\,\mathbf{u}_c(k) \tag{20}$$

$$\begin{cases}\text{Prob}\{\alpha_1(k)=1\}=E\{\alpha_1(k)\}=\alpha\\ \text{Prob}\{\alpha_1(k)=0\}=1-\alpha\\ \text{Prob}\{\alpha_2(k)=1\}=E\{\alpha_2(k)\}=\beta\\ \text{Prob}\{\alpha_2(k)=0\}=1-\beta\end{cases} \tag{21}$$

Here $0<\alpha,\beta\leq 1$.

To simplify the equation of state based on data packet loss, another random number sequence $e(k)$ was introduced

$$\begin{cases} e(k) = \alpha_1(k)\alpha_2(k) \\ \text{Prob}\{e(k) = 1\} = E\{e(k)\} = \bar{e} = \alpha\beta \\ \text{Prob}\{e(k) = 0\} = 1 - \alpha\beta \end{cases} \tag{22}$$

Here, $0 < \bar{e} \leq 1$.

Equation (20) can now be rewritten into the following form

$$\mathbf{x}_c(k) = \alpha\beta\mathbf{x}(k) + (1 - \alpha\beta)\mathbf{x}(k-1) \tag{23}$$

Consider the following state feedback controller

$$\mathbf{u}(k) = \mathbf{K}(k)\mathbf{x}_c(k) \tag{24}$$

Here, $\mathbf{K}(k)$ was the controller gain that needed to be designed.

Therefore, the equation (16) was organized into the following form

$$\begin{cases} \mathbf{x}(k+1) = [\mathbf{A}\delta(k) + \alpha\beta\mathbf{BK}(k)]\mathbf{x}(k) \\ \qquad + (1 - \alpha\beta)\mathbf{BK}(k)\mathbf{x}(k-1) \\ \qquad \mathbf{y}(k) = \mathbf{Cx}(k) \end{cases} \tag{25}$$

In this paper, the output feedback robust predictive control is adopted. The output feedback is a robust model predictive control (RMPC), which is represented by a robust predictive compensation algorithm combining the robust predictive controller and the output feedback controller.

B. ROBUST MODEL PREDICTIVE CONTROL (RMPC)

First, define $\mathbf{x}(k+i|k)$ and $\mathbf{y}(k+i|k)$ as the predicted value of the system at time k to time $k+i$.

$$\mathbf{u}_c(k+i|k) = \mathbf{K}(k)\mathbf{x}_c(k+i|k), \quad i = 0, 1, 2, \cdots \tag{26}$$

The performance indicators considering RMPC follow:

$$J_\infty(k) = \max_{\delta(k+i)\in\Delta, i\geq 0} E\left\{\sum_{i=0}^{\infty}\left(\left|\mathbf{x}(k+i|k)^2_Q + \mathbf{u}(k+i|k)^2_{\mathbf{R}}\right|\right)\right\} \tag{27}$$

Here $\mathbf{Q}$ and $\mathbf{R}$ are a symmetric positive definite matrix.

C. PREDICTIVE CONTROLLER DESIGN

Assume that the state of the discrete control system is measurable, $\mathbf{x}(k|k)$ is the state quantity of the system measured at time k, and the input and output of the system are unconstrained. If a given symmetric positive definite matrix is satisfied $\mathbf{Q} > 0$, $\mathbf{R} > 0$, and $Z_j, G_j, X_j > 0$, $\gamma > 0$, then the packet loss compensation strategy makes the performance index of the RMPC upper bound as $V(k|k)$ satisfies Equation (28) and (29).

$$\begin{bmatrix} 1 & * \\ \mathbf{x}(k|k) & X_j \end{bmatrix} \geq 0, \quad j = 1, 2, \cdots, L \tag{28}$$

$$\begin{bmatrix} G_j^T + G_j - X_j & * & * & * & * \\ A_jG_j + \bar{e}BZ_j & X_l & * & * & * \\ \sqrt{\bar{e}(1-\bar{e})}BZ_j & 0 & X_l & * & * \\ \sqrt{Q}G_j & 0 & 0 & \gamma I & * \\ \sqrt{\bar{e}}RZ_j & 0 & 0 & 0 & \gamma I \end{bmatrix} > 0 \tag{29}$$

where $j = 1, 2, \cdots, L, \quad l = 1, 2, \cdots, L$.

In addition

$$J_\infty(k) \leq V(k|k) \leq \gamma \tag{30}$$

$$V(k+i|k) = |x(k+i|k)|^2_{P(\delta(k+i))} \tag{31}$$

$$P(\delta(k+i)) = \sum_{j=1}^{L}\lambda_j(\delta(k))P_j \tag{32}$$

$$P_j = \gamma X_j^{-1} \tag{33}$$

The packet loss compensation controller feedback matrix is given as:

$$\mathbf{K}(k) = \sum_{j=1}^{L}\lambda_j(\delta(k))\mathbf{K}_j \tag{34}$$

and

$$K_j = Z_jG_j^{-1} \tag{35}$$

The operational flow of the RMPC algorithm was:

Step 0: Set $k = 0$.

Step 1: Measure $\mathbf{x}(k|k) = \mathbf{x}(k)$ and $\delta(k)$.

Step 2: If $\mathbf{x}(k|k)$ is transferred from the actuator to the controller, then solve the optimization problem $\min_{G_j,X_j,Z_j} \gamma, s.t.41, 42$, and calculate $\mathbf{K}(k)$; otherwise, go to Step 4.

Step 3: Apply the control amount $\mathbf{u}(k) = \mathbf{K}(k)\mathbf{x}(k)$ to the control system.

Step 4: Set $k = k+1$, and go to Step 1.

The space state equation of the powertrain system distributed test platform is shown in Equation (1), and the state equation is discretized, as shown in Equation (36).

$$\mathbf{x}(k+1) = \mathbf{A}(\alpha(k))\mathbf{x}(k) + \mathbf{B}(k)\mathbf{u}(k) \tag{36}$$

Since the Internet-based powertrain system has no uncertainty parameter, $\alpha(k)$ can be a constant, and Equation (36) can be organized into

$$\mathbf{x}(k+1) = \mathbf{Ax}(k) + \mathbf{Bu}(k) \tag{37}$$

D. SIMULATION ANALYSIS

To set the initial state vector $\mathbf{x}^T = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$, the simulation duration is 1800 s, the sampling period is 0.001 s, and the symmetric positive definite matrix is given as

$$\mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix} \tag{38}$$

When $\bar{e} = 0.5$ was set, the system was simulated and analyzed. The simulation results were used to obtain the success of the data packet transmission during the system simulation process, as shown in Figure 5.

Another important result of the simulation was the value of the state feedback compensator K as shown in Figure 6.

The effects of system simulation on the stability of the system under the action of an RMPC based on state feedback compensation are shown in Figures 7 and 8.

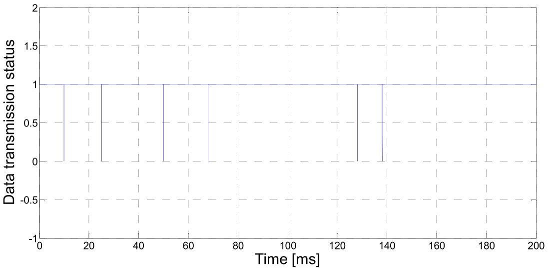

FIGURE 5. Data packet loss status.

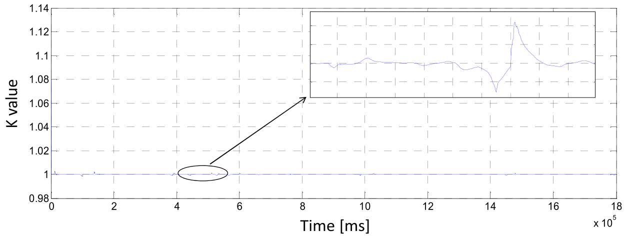

FIGURE 6. Value of the state feedback compensator ***K***.

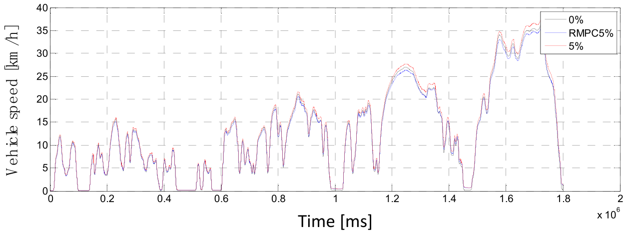

FIGURE 7. Relationship between 5% data packet loss rate (PLR) and 0 PLR as well as vehicle speed.

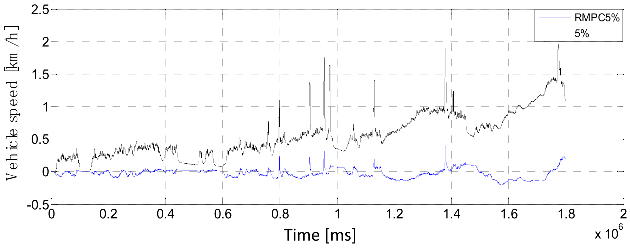

FIGURE 8. Speed difference of 5% data PLR and 0 PLR.

As shown in Figure 7, in the case of a data packet loss rate (PLR) of 5%, during the entire test period, after the optimization of RMPC, the output vehicle speed was close to the output speed of the ideal state. To compare the optimization effect, the output vehicle speed in the ideal state was taken as the reference vehicle speed. For the data PLR of 5%, the differences between the speed of RMPC, the unoptimized speed, and the reference vehicle speed are shown in Figure 8. The optimization strategy of RMPC made the difference between the output vehicle speed, and the reference vehicle speed fluctuated around 0. Compared with the unoptimized state, the optimization effect is more obvious.

To further analyze the optimization effect of RMPC, this paper compares the difference between the output speed of RMPC and the reference vehicle speed, and the difference between the output speed of the non-robust predictive compensator and the reference vehicle speed, and then plots the speed optimal values, as shown in Figure 9.

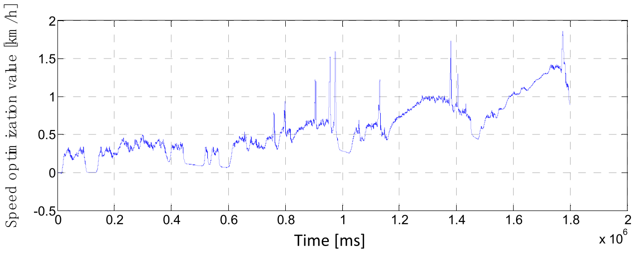

FIGURE 9. RMPC optimization quality.

Figure 9 shows RMPC playing an optimization role in the low-speed, medium-speed, high-speed and ultra-high-speed sections of the test conditions. The degree of optimization also increased with the increase of the vehicle speed, especially in the ultra-high-speed section. The optimization strategy of RMPC played a significant role, and the maximum optimized amplitude reached 2 km/h.

As seen in Figures 7, 8, and 9, when the control system was connected with the Internet, if the system had a data PLR of 5%, the stability of the system was greater with RMPC strategy.

V. CONCLUSION

The Internet-based distributed test platform is a development trend of future vehicle test validation. The reliability of the test platform is an important research direction for the distributed test platform. In this paper, the theoretical and simulation analysis of data packet loss on the stability of Internet-based distributed test platforms during Internet data transmission was carried out. The analysis found that data loss had an impact on vehicle speed over the entire test system. Especially when the data PLR exceeded 5%, the impact on system stability could not be ignored. The results of this study provide a powerful theoretical basis for the optimal design of Internet-based distributed test platforms.

Based on this research, a robust model predictive compensator with state compensation was designed. Under the action of the predictive compensator, its optimization ability for the Internet-based distributed test platform was validated by simulation analysis. RMPC effectively improved the stability of the system. Compared with the Internet-based distributed test platform without the predictive compensator, it greatly improved the system performance of the Internet-based distributed test platform.

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