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Cloud-based adaptive semi-active suspension control for improving driving comfort and road holding

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Abstract: The improvement of driving comfort and vehicle stability performance is essential for the vehicles, which can be actualized by adaptive semi-active suspension control. Cloud computing allows several features for autonomous vehicles. Implementing the adaptive suspension control using historical road data gathered in the cloud database is one of these features. This paper deals with the adaptive semi-active suspension control from the perspective of a Vehicle-to-Cloud-to-Vehicle integration. Measured and historical performance(vertical acceleration and tire deformation) and velocity data in different locations and road irregularities from other vehicles have been stored in the cloud database and used to design the dedicated scheduling variable. The novelty of this paper is developing the adaptive semi-active suspension control method with different scheduling parameter design approaches based on cloud application for the road adaptation capabilities of the suspension system. The control architecture is founded on the Linear Parameter-Varying framework, where the scheduling variable allows the trade-off between driving comfort and vehicle stability. The real data simulation demonstrates the operation of the introduced method in the TruckSim simulation environment and Matlab/Simulink. The results show that both vehicle stability and driving comfort has been improved.

Keywords: Adaptive semi-active suspension control, cloud computing,improving driving comfort, improving road holding

1. INTRODUCTION

Cloud computing is a significant technology for the application of advanced vehicle control and optimization computation. Autonomous vehicles have advanced technology consisting of numerous embedded electronic control units, and control of these units needs high computing power and storage. But this computing power and storage is not cost-effective, due to this reason, cloud computing is an effective solution for the high algorithm load and database complexity.

There are several criteria for the autonomous driving, while safety is the most important one. Nevertheless ensuring driving comfort is also a significant performance development on the control design. Controlling the vertical dynamics of the vehicle increase comfort level of passenger. Due to that a well-designed suspension system radically improves both road holding and driving comfort. The road condition and irregularity are needed to be known and analyzed in order to design adaptive vertical control of autonomous vehicles. The road condition can be estimated with several methods Qin et al. (2018); Göhrle et al. (2014) or the cloud-based database can be used in order to know the road conditions Basargan et al. (2021b). The reconfigurable control method is needed in order to change controller behavior for different external factors such as velocity, road condition, and road irregularity, etc. This control approach finds the trade-off between vehicle safety and driving comfort. The reconfigurable control is based on the velocity of vehicle, road condition and performance importance of the vehicle.

There are numerous researches where the development of the semi-active suspension system based on the quarter-car model has been studied with different approaches and techniques. The most common control strategy is a skyhook Savaia et al. (2021); Negash et al. (2021). The implementation of this method is easy; however, it disrupts the dynamic tire load. The linear-quadratic (LQ) control improves both driving comfort and road-holding, but the full state measurement or estimation are required. The model predictive control (MPC) Hegedűs et al. (2021); Nguyen et al. (2016) method is also widely used, but it

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lacks robustness properties. It is crucial to guarantee the ride comfort and vehicle stability performances, where it is allowed by H_∞ control method Zin et al. (2005); Rossi and Lucente (2004); however, the reconfiguration of this controller in real-time is not possible due to the fixed weighting of the performances. It is needed to use the control method, which allows the online reconfiguration of the control system in order to react differently for particular road irregularities and categories. Due to this reason, the semi-active suspension control is founded on the Linear Parameter Varying (LPV) framework, as already introduced in Basargan et al. (2021a); Basargan et al. (2021), where it is possible to reconfigure the controller during operation.

There are several methods to find more efficient and performance-related cloud-aided suspension system control in the literature. Most of them try to estimate and preview the road profile by the camera, radar, or lidar information Liu et al. (2020) while some approaches consider this problem by using low-end sensors such as potentiometers and accelerometers Tomizuka (1976). However, it is possible to store the estimated road profile in maps and share it with other vehicles via cloud Li et al. (2014, 2015). This study proposes a cloud-aided system, where the road data is collected by vehicles, and this data is stored for usage to other vehicles. The road data consists of the type and size of road irregularities, location of the road irregularities, and performance results of the vehicle in these locations.

This study introduces the novel method of a cloud-based adaptive semi-active suspension control system with different scheduling variable designs in cloud computing. The reconfigurable semi-active suspension system has been developed using Vehicle-to-Cloud-to-Vehicle(V2C2V) technology, where adaptation of the vehicle for the road irregularities is possible in different performance orientations according to type and level of road irregularities. The advantage of the proposed methodology is cost-efficient system adaptation and control without hardware-related technology. The scientific contribution of this study is to integrate cloud systems in the control process of the semi-active suspension with different scheduling variable designs for different road vehicles.

The paper is organized as follows: Section 2 presents the modeling of the control-oriented quarter-car suspension and LPV controller synthesis. Section 3 describes the integration of the system, architecture of cloud system, and decision algorithm for the scheduling variable. Section 4 demonstrates the operation of the proposed cloud-aided control method in the TruckSim simulation environment with real road data. Finally, concluding remarks are presented in Section 5.

2. CONTROL SYNTHESIS

The modeling of the control-oriented quarter-car suspension and reconfigurable semi-active suspension control design through the LPV method have already been introduced in Basargan et al. (2021); just some points have been modified and explained in this study.

The performance specifications are defined as follows: The criterion z_1 procures the minimization of body acceleration to improve passenger comfort($z_1 = \ddot{z}_s \rightarrow 0$). Suspension deflection minimization provides a guarantee for the stability of the vehicle with z_2 criterion($z_2 = (z_s - z_{us}) \rightarrow 0$). Minimizing the dynamics tire load for the stability with z_3 criterion($z_3 = (z_{us} - w) \rightarrow 0$) otherwise the control force must be considered with criterion $z_4 = F \rightarrow 0$. The performance vector is written as $z = \begin{bmatrix} z_1 & z_2 & z_3 & z_4 \end{bmatrix}^T$.

It is necessary to define the scheduling variable $\rho \in [0.01, 0.99]$ to shape the performance weighting functions (W_{pd}, W_{pa}, and W_{pt}) in order to guarantee the control configuration in case of the predefined performances become more significant by reason of estimated oncoming road conditions. These weighting functions are shown in 1, while other weighting functions are in a similar proportional and linear form without any scheduling variable.

$$\begin{aligned} W_{p_a} &= \rho \frac{\alpha_1 s + 1}{T_1 s + 1} \\ W_{p_d} &= (1-\rho) \frac{\alpha_2 s + 1}{T_2 s + 1} \\ W_{p_t} &= (1-\rho) \frac{\alpha_3 s + 1}{T_3 s + 1}, \end{aligned} \tag{1}$$

where, $T_{1,2,3}$ and $\alpha_{1,2,3}$ are design parameters.

This introduced design is a reconfigurable LPV controller, where $\rho = 0.01$ stands for road holding and vehicle stability and $\rho = 0.99$ stands for the performance of driving comfort. Between these edge values, a mixed performance is given. The details of control design can be found in Basargan et al. (2021).

3. CLOUD SYSTEM INTEGRATION AND DECISION ALGORITHM

Architecture of the system, designing of the scheduling variable and integration of the cloud application is described in this section.

3.1 System architecture and cloud application

The capabilities of the cloud, database, and computing technologies are used in order to improve the comfort and safety of such equipped vehicles in this study. The system consisft of three different subsystem, that are semi-active suspension system with MR damper, controlled by the LPV controller explained in the previous section; the cloud system communicates with the vehicle and gathers, processes, stores and distributes the data. The architecture of the proposed system is shown in Fig. 1

The general-purpose V2C2V architecture is illustrated in Fig. 2. Vehicles are connected to the internet with the wireless networks. The cloud system provides access to the database as needed for cloud computing and designing the scheduling variable. The cloud system can provide huge computing power, its use for vehicle control is limited by the availability of the network. Sensors provide required data from vehicles, raw and processed data can be transmitted to the cloud system for computing and reaching the database Li et al. (2015).

The process of decision making for the scheduling parameter in the cloud system is the following:

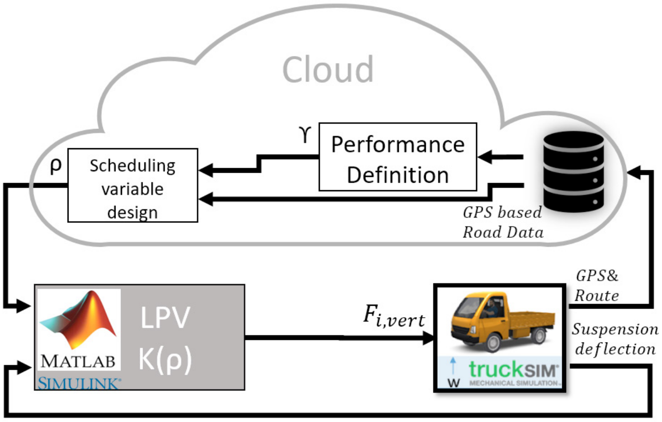

Fig. 1. System architecture

Fig. 2. V2C2V architecture

- numerous measurement data is collected by the onboard unit from the passive suspension system and this measurement data is uploaded to the cloud system.
- the database, which is consist of the road information is build by gathering information from vehicles by the developed cloud application.
- the performance index is defined in order to find importance between driving comfort and road holding in the cloud application.
- according to road irregularity, vehicle velocity, performance results and performance index, the corresponding scheduling variable is calculated in the related location by the decision algorithm in the cloud.
- the calculated scheduling variable is used in the LPV controller to modify the behavior of the LPV controller.
- the corresponding damper force is forwarded to the damper of the vehicle.

The cloud part of the system is implemented on a private infrastructure cloud. It is also possible to implement the introduced architecture on the other clouds with minor modifications. The selected database engine is MongoDB due to its handling geospatial information feature. The cloud application uses a Flash framework for providing a RESTful API to the cloud functionality and written in Python Basargan et al. (2021b).

TruckSim software is used to simulate the simulation vehicle, while the environment has been integrated with Matlab/Simulink. Here, a test of controller and cloud connection via web API is possible. This integration is depicted in Fig.1.

Following steps are followed to design the scheduling variable: defining performance index Υ to find out consideration of the performance criteria, and then the scheduling variable is designed with the mathematical approach by using the performance index. The onboard computer collects the current velocity, vehicle position, vertical acceleration of the body, and deformation of the tire. These collected parameters are transmitted to the cloud application via a mobile internet connection.

3.2 Scheduling variable design

The scheduling variable design is based on the comparison of performance results in corresponding velocity and road irregularity in the cloud database. First, the performance index is calculated based on the previous measurement of the vehicles that have passive suspension. The importance of one of vertical acceleration and tire deformation performances is selected depending on their value. Once new data arrives, the cloud application calculates the dedicated scheduling variable for the controller.

Cloud-based road database has numerous measurements and historical data with different velocities and road irregularities. These measurement and data consist of type and size of road irregularity, the location of road irregularity, velocity of the vehicle, tire deformation value and vertical body acceleration value at each time step. It is necessary to group all these data in order to use them in comparison with the new arrived data from onboard computer. Thus, root-means-square (RMS) of vertical body acceleration and tire deformation has been calculated by Eq. 2.

$$
\begin{aligned}
R^{va} &= \sqrt{\frac{1}{T_a}\int_0^{T_a} a^2(t)dt} \\
R^{rd} &= \sqrt{\frac{1}{T_t}\int_0^{T_t} {t_d}^2(t)dt}
\end{aligned}
\tag{2}
$$

where, R^{td} and R^{va} are RMS of the tire deformation and vertical acceleration, while $a(t)$ and $t_d(t)$ are the timeweightedvertical acceleration and tire deformation, $T_{a,t}$ is the number of acceleration and tire deformation. Their normalized value is calculated as follow:

$$
\zeta^k_{i,j} = \frac{100R^k_{i,j}}{R^k_{max}} \tag{3}
$$

Here, ζ is normalized value, $k \in [va, td]$is performance, where td is tire deformation and va is vertical acceleration performance, i is type of road irregularity and j is velocity of the vehicle. In the case of the velocity of the simulated vehicle which differs from the cloud, the interpolation method is used to find dedicated performance values for different velocities and irregularities. The set of example cloud data is shown in Table 1.

The first step to design the scheduling variable is finding the performance index, where defining the importance between two performances is possible. The comparison of their normalized value gives the result of the Υ.

$\Upsilon = 1$ stands for the driving comfort consideration(vertical acceleration), $\Upsilon = 0$ stands for road holding consideration(tire deformation) and both performance consideration is defined as $\Upsilon = 0.5$. This consideration can be defined as the distance of the scheduling variable from 0.5. If the performance index defines the consideration as vertical acceleration, ρ should be close the one, while it defines the consideration as tire deformation, scheduling variable should be close to zero. The selection of performance index is shown in Eq. 4 describes selection of the performance index.

$$\Upsilon = \begin{cases} 0, & \text{if} \quad \zeta^{td} > \zeta^{va} \\ 1, & \text{if} \quad \zeta^{td} < \zeta^{va} \\ 0.5, & \text{if} \quad \zeta^{td} = \zeta^{va} \end{cases} \tag{4}$$

Next, the scheduling variable ρ is calculated depends on the performance index and performance results in corresponding road irregularity and velocity. This calculation is handled by Eq. 5.

$$\rho = \begin{cases} 0.5 - \kappa, & \text{if} \quad \Upsilon = 0 \\ 0.5 + \kappa, & \text{if} \quad \Upsilon = 1 \\ 0.5, & \text{if} \quad \Upsilon = 0.5 \end{cases} \tag{5}$$

Here, κ is shifting index which defines the distance of the corresponding scheduling variable from 0.5. This index is defined according to rate index χ which is calculated by the average rate between normalized value of tire deformation and vertical acceleration in the cloud, while this value is calculated as 2 according to data in the cloud. It means that, if rate of corresponding normalized performance value is greater than two, shifting index κ is 0.5. Because, κ cannot be greater than 0.5 due to scheduling variable limitation($\rho \in [0.01, 0.99]$).

$$\kappa = \begin{cases} 0.5, & \text{if} \quad \dfrac{\zeta^{td}}{\zeta^{va}} \vee \dfrac{\zeta^{va}}{\zeta^{td}} >= \chi \\ \dfrac{\zeta^{td}}{\zeta^{va}} 0.25, & \text{if} \quad \zeta^{td} > \zeta^{va} \\ \dfrac{\zeta^{va}}{\zeta^{td}} 0.25, & \text{if} \quad \zeta^{va} > \zeta^{td} \end{cases} \tag{6}$$

In the case normalized tire deformation is greater than normalized vertical acceleration, the rate of normalized tire deformation and vertical acceleration has been used to calculate κ. The value of 0.25 restricts the κ value between 0 and 0.5.

4. SIMULATION RESULTS AND ANALYSIS

The selected vehicle for the simulation is compact utility truck that has independent rear and fron semi-active suspension. The Hungarian highway road had been implemented in TruckSim vehicle simulation environment based on real geographical data with road distortions and velocity limits. The simulated route has been shown in Fig. 3.

Table 1. Cloud database

Road Irregularity	Vel.	R^{va}	ζ^{va}	R^{td}	ζ^{td}
Roughness	20	0,0302	2,28	0,0005	4,55
	40	0,0564	4,25	0,0014	12,73
	60	0,0804	6,06	0,0019	17,27
	80	0,1093	8,24	0,0031	28,18
3 cm bump	20	0,0352	2,65	0,0005	4,55
	40	0,0706	5,32	0,0013	11,82
	60	0,134	10,11	0,0022	20,00
	80	0,19	14,33	0,0032	29,09
3 cm pothole	20	0,0351	2,65	0,0005	4,55
	40	0,071	5,35	0,0013	11,82
	60	0,134	10,11	0,0022	20,00
	80	0,188	14,18	0,0032	29,09
5 cm bump	20	0,058	4,39	0,0005	4,54
	40	0,115	8,71	0,0012	10,90
	60	0,217	16,41	0,0022	20,00
	80	0,293	22,15	0,0033	30,00
5 cm pothole	20	0,0581	4,38	0,0005	4,54
	40	0,1165	8,78	0,0013	11,82
	60	0,2178	16,42	0,0022	20,00
	80	0,29	21,87	0,0032	29,00
7 cm bump	20	0,081	6,11	0,0005	4,54
	40	0,16	12,06	0,0013	11,80
	60	0,291	21,94	0,0022	20,00
	80	0,401	30,24	0,0033	30,00
7 cm pothole	20	0,081	6,10	0,0005	4,54
	40	0,1625	12,25	0,0013	11,80
	60	0,3091	21,31	0,0022	20,00
	80	0,4784	36,07	0,0033	30,00
10 cm bump	20	0,115	8,71	0,0013	11,80
	40	0,217	16,40	0,0022	20,00
	60	0,293	22,10	0,0033	30,00
	80	0,537	40,50	0,0036	35,40
12 cm bump	20	0,1392	10,50	0,0006	5,45
	40	0,245	18,48	0,0014	12,73
	60	0,5509	41,55	0,003	27,27
	80	0,7468	56,32	0,0056	50,91
Multiple bumps & potholes (5cm)	20	0,37	27,90	0,011	100
	40	0,431	32,50	0,0017	15,40
	60	0,466	35,20	0,0029	26,30
	80	0,444	33,50	0,0041	37,20
Multiple bumps & potholes (7cm)	20	0,3769	28,42	0,0012	10,91
	40	0,4902	36,97	0,0018	16,36
	60	0,6506	49,06	0,0034	30,91
	80	0,6644	50,11	0,0047	42,73
Sine-sweep	20	0,431	32,50	0,007	63,60
	40	0,751	56,60	0,002	21,80
	60	1,122	84,60	0,003	27,20
	80	1,326	100,00	0,011	100

The route is 3400 m long with different road irregularities depicted in 2. The selection of road irregularities is based on real road scenarios and gives maximal stress to the suspension. The roughness of road irregularity between 2.1 mm and -2.6 mm expresses the distortion on the asphalt, and they are common in the alley, side streets, and rural areas. The 10 cm heightened left, and right side bumps represent common speed bumps in urban areas, and driving over a speed bump can be analyzed with this irregularity. The several bumps, that have bumps and

Table 2. Irregularities and designed scheduling variable

Road Irregularity	**Velocity (km/h)**	**Location (m)**	ρ
12 cm pothole	65	120	0.8847
Roughness	60	455	0
Multiple 5cm irregularities	70	900	0.8346
Multiple 7cm irregularities	70	1300	0.89
Sinusodial irregularity	75	1800	0.5
3cm bump	75	2200	0
7cm pothole	70	2800	0.7664
10cm bump	80	3200	0.7860
5cm pothole	80	3300	0.1685

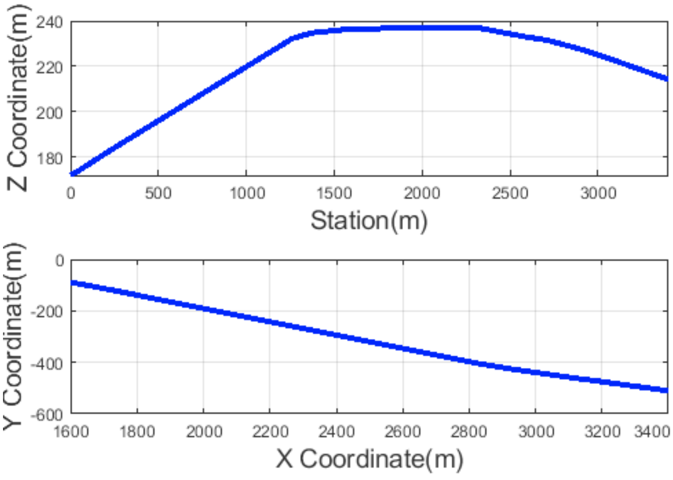

Fig. 3. Simulation route

potholes following each other differently on the right and left side of the lane, having 5 cm and 7 cm depth and height represent bad road quality with discontinuities in the asphalt. The sine-sweep distortion that represents a typical road at bus stops because of its rolled-up structures is a longitudinal sinusoidal road distortion with growing frequency, and it puts high stress on the suspension system.

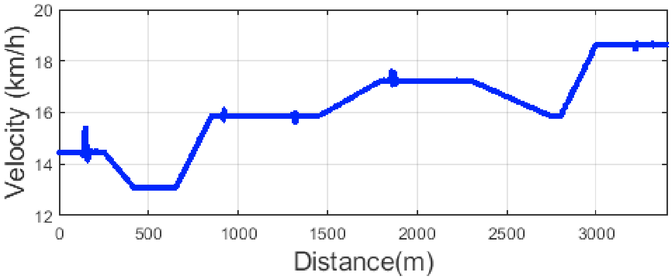

Fig. 4. Velocity profile of vehicle

Two different simulations are designed to demonstrate the effectiveness of the introduced method: first one with the conventional semi-active suspension and other one with introduced cloud-based adaptive semi-active suspension. Both vehicles are utility truck and their velocity profile can be seen in Fig. 4.

The result of the cloud computing for the selection of scheduling variable be observed in Fig. 5, where these results can also be seen in Table 2.

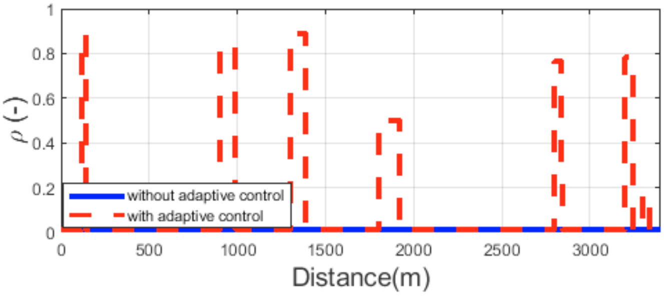

Fig. 5. Designed scheduled variable

The results of non-adaptive and cloud-aided adaptive method are compared in order to evaluate the performance efficiency. Please note that upper figure shows non-adaptive, below figure shows adaptive method. It is well demonstrated that both lateral and vertical accelerations have been decreased at the road distortions with the introduced method, which significantly improves driving comfort, see Fig. 6.

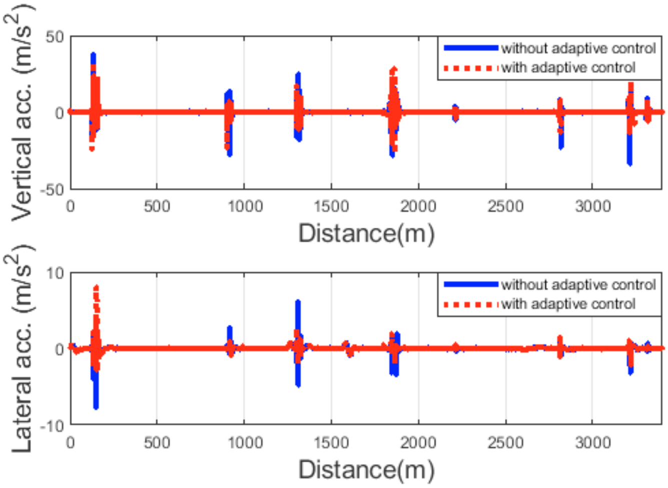

Fig. 6. Vertical acceleration

Otherwise, tire deformation shown in Fig. 8 and suspension deflection depiced in Fig. 7 has also been reduced, due to improvement on road holding and stability with the proposed method. The introduced method didn't affect the performance of the vehicle for irregularity of 3 cm bump and roughness due to its scheduling variable that is zero, where the comparison with non-adaptive scenarios also has the same scheduling variable.

5. CONCLUSION

This study introduced a new cloud-aided adaptive semi-active suspension system, adapting the performance of controller to upcoming road conditions to improve driving and safety performances. The road irregularity and velocity information, along with dynamic vehicle signals, had been gathered and stored in the cloud database by previous journeys of the vehicle in the related road. The corresponding scheduling variables for specific road irregularity and velocity have been computed in the cloud. This

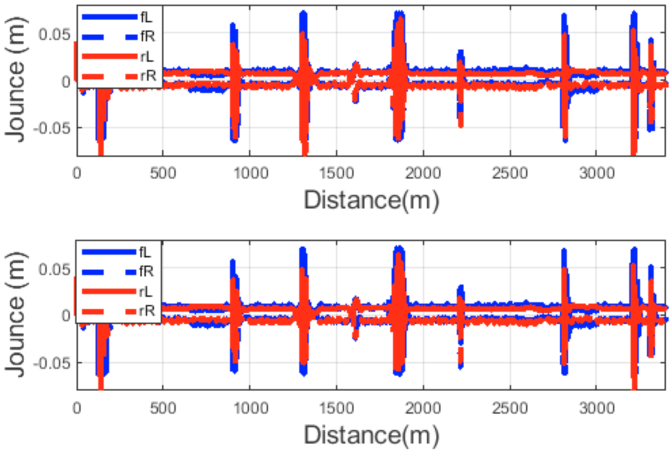

Fig. 7. Suspension deflection

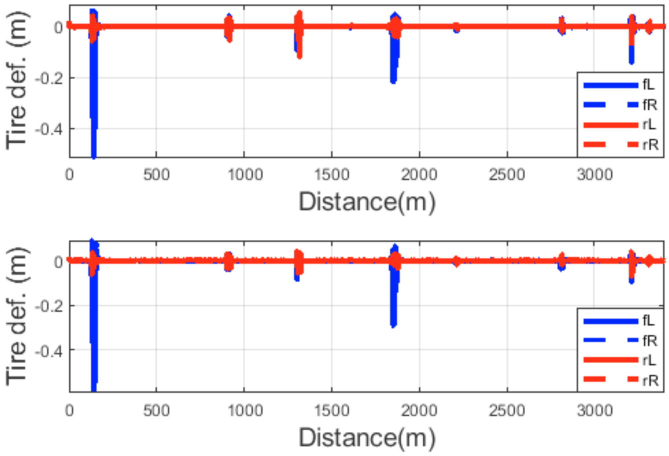

Fig. 8. Tire deformation

new method for scheduling variable computing depends on the type and level of road irregularity and velocity of the vehicle. By this means, the semi-active suspension system is able to adapt in coherence with oncoming road conditions and current velocity, where this method improves both driving comfort and vehicle stability. The LPV method has been used in the control design. An operation of the introduced method has been demonstrated in the TruckSim. The results of simulation show that both vehicle stability and driving comfort have been improved.

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