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Dynamic Behavior Analysis of the Bus with Two-stage Asymmetric Damper Using the Quarter Car Model Subjected to Transient Road Profile

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ABSTRACT

The influences of two-stage asymmetric damper on the dynamic responses under transient road inputs in range of different vehicle velocities were investigated. This study's purpose is to get full understanding of the dynamic behavior of the bus using the two-stage asymmetric damper. The body's vibration acceleration, the tire dynamic load coefficient, and the suspension dynamic deflection were all analyzed to determine how much vibration was conveyed to the bus. By evaluating these criteria, this paper shows how the two-stage asymmetric damper affected an inner-city bus's vibrational behavior. The transient input was employed in accordance with the GB/T 4970-2009 and IRC-99-1988 standards. For the purposes of the investigation, the two degrees of freedom quarter car model has been employed to carry out the simulation. According to the analysis's findings, a two-stage asymmetric damper maintains the better ride comfort level but offers the bus less handling stability and working space than a linear symmetric one.

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1. Introduction

Due to the number of vehicles is constantly rising in community, the energy and environmental challenges are becoming more critical in recent years. Those issues may be resolved by using public transportation, especially by using inner-city bus in metropolitan. Occupants' comfort, performance, and health are significantly impacted by vibration transmission to bus during a journey [1]. A comfortable ride is a requirement for an inner-city bus, in order to attract passengers and encourage more and more individuals to use them for daily commutes. Because of the constrained structure, massive cost, and demanding working conditions of inner-city buses, the suspension design should be thoroughly investigated to minimize the negative impacts of vibrations and assure the satisfaction of the customer of public transport services.

Recently, measurements of a vehicle's vibration levels in actual driving situations have been carried out not only to analyze how comfortable the ride is, but also to evaluate the suspension's effectiveness when vibrations are transferred from the wheels to the vehicle's body [2]. For instance, the vibration levels have been measured in its real operating condition based on the data from the sensor mounted on the vehicle, and evaluations have been made [3]. Another research has collected vibrational signals from passenger's smartphones and the results of analysis will be shown on screens along the bus. In case of exceeding the permitted threshold (in accordance with ISO 2631-1:1997), the system will sound an alarm [4].

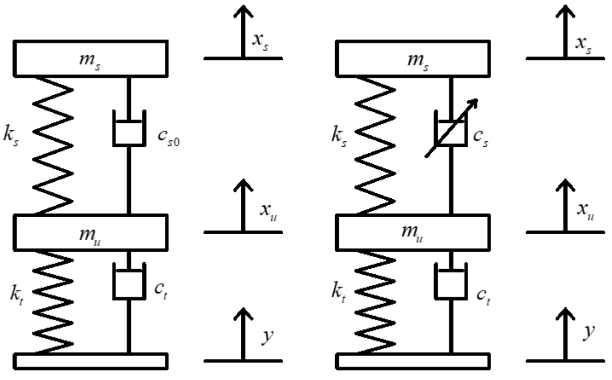
When acquiring vibrational data might be difficult due to various mechanical limitations, simulated analysis using a vehicle vibrational model is an effectively alternative to collecting real-time data [5]. Simulations become increasingly crucial for reducing expenses when measurements are difficultly conducted due to a range of different of mechanical limitations. Numerous studies have attempted to identify the optimal damper parameter that compromise among ride comfort, suspension deflection, and road-holding stability criteria. The driver's body vertical acceleration, suspension deformation, and dynamic wheel load were examined using a linear oscillatory bus model to determine how spring stiffness and shock absorber damping influenced these quantities [6]. More complex vehicle models are built with a ten DOFs model to identify a set of seat oscillatory parameters that would significantly improve the driver's comfort [7]. An approach has been introduced for the optimum design of the vehicle suspension system, taking into account a whole vehicle model with 11-DOF in order to enhance ride comfort, road holding, working space, and avoiding rollover [8]. However, these studies have ignored the nonlinear characteristic of damper that a common damper would generate larger rebound damping force than compression one [9]. Many studies have developed a nonlinear damper model with linear asymmetric characteristic and the results showed the clear difference of dynamic response between linear symmetric damper and linear asymmetric one. For example, the linear symmetric damper helps to reduce vehicle body vibration acceleration and suspension dynamic deflection under triangular bump excitation when compared to the linear asymmetric one [10]. The behavior of two distinct kinds of shock absorbers, linear symmetric and linear asymmetric, has been investigated, and the findings demonstrate that using asymmetrical systems might be a more favorable selection for reducing levels of vibrational acceleration [11]. Nonetheless, these damper models are still simple for representing the nonlinear characteristic of a real absorber.

Motivated by the above observations, this paper employs the quarter car model with a complicated damper model, in which the two-stage asymmetric damper, to attempt to highlight the difference responses between two-stage asymmetric damper and linear symmetric one when the bus is subjected to transient road profiles which is extremely popular for limiting speed in city. The suspension's performance was analyzed based on the evaluation indices including body's vibration acceleration, suspension dynamic deflection, and tire dynamic load coefficient. The obtained results and the conclusion have been made for getting full insight into damper's nonlinear characteristic.

2. Theory and simulation model

2.1. Quarter car model

A quarter car model, which are widely employed in automotive engineering because they are straightforward and provide reliable information, at least during the initial design phases of vehicle dynamics [12], is shown in Figure 1. This 2-DOFs model are made up of the tire wheel, the suspension components, the quarter of the chassis, and these are rigidly connected. The characteristics employed in the simulation model are shown in Table 1 along with an explanation of the parameters from Figure 1.



(a) *(b)*

Figure 1. *A quarter car model with two kinds of damper [13]: (a) Symmetric damper; (b) Asymmetric damper*

The system's differential vibrational equations in matrix form are shown as follows, Equation (1):

$$M\ddot{x} + C\dot{x} + Kx = f(t) \tag{1}$$

where: $x(t) = (x_u \ \ x_s)^T$ illustrates the response vector.

$$\mathrm{M} = \begin{bmatrix} m_u & 0 \\ 0 & m_s \end{bmatrix},\ \mathrm{C} = \begin{bmatrix} c_s + c_t & \text{-}c_s \\ \text{-}c_s & c_s \end{bmatrix},\ \mathrm{K} = \begin{bmatrix} k_s + k_t & \text{-}k_s \\ \text{-}k_s & k_s \end{bmatrix},\ f(t) = \begin{bmatrix} k_t y + c_t \dot{y} \\ 0 \end{bmatrix} \tag{2}$$

Identify the mass, damping coefficient, stiffness and external force matrices, respectively.

In the model using a two-stage asymmetric damper, the suspension damping coefficient c_s varies among a range of distinct values.

In Table 1 below, a bus parameter is shown.

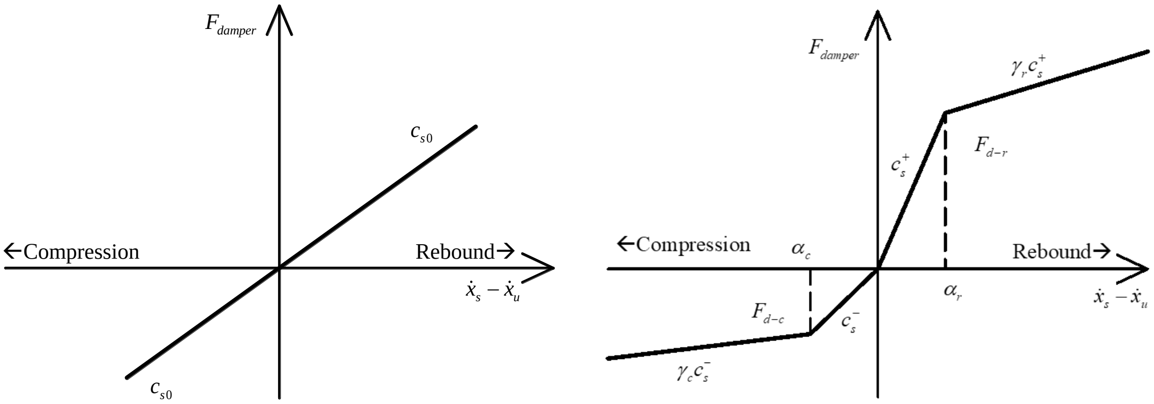
Table 1. *Bus parameter*

Bus parameter	**Symbol**	**Value**
Sprung mass	m_s	2000(kg)
Un-sprung mass	m_u	250(kg)
Natural frequency	f_n	1.0(Hz)
Damping ratio	ξ	0.4
Spring stiffness	k_s	85799(N/m)
Tire stiffness	k_t	1000000(N/m)
Equivalent linear damping coefficient	c_{s0}	10053(Ns/m)
Two-stage damping coefficient	c_s	Dependence on asymmetric characteristic
Tire damping coefficient	c_t	150(Ns/m)

This is the technical parameters of a typical bus in Vietnam, the above parameters are appropriate for representing the typical bus's parameters.

2.2. Conceptual model of two-stage asymmetric damper

As illustrated in Figure 2, the suspension damper, in which the two-stage asymmetric characteristic in the compression and rebound, is taken into account [14].



(a) *(b)*

Figure 2. *The relation between damper's relative velocity and damping force: (a) Linear symmetric damper; (b) Two-stage asymmetric damper*

where:

c_s^- : Compression damping coefficient, c_s^+ : Rebound damping coefficient.

$\beta = \dfrac{c_s^+}{c_s^-}$ is the asymmetric ratio.

The relationship between equivalent linear damping coefficient and two-stage damping coefficient, by assuming that the linear and two-stage asymmetric dampers dissipate energy similarly, is shown in Equation (3) [14]:

$$c_{s0} = \frac{c_s^-(1+\beta)}{2} = \frac{c_s^+(1+\beta)}{2\beta} \tag{3}$$

According to this relationship, the asymmetric damping force will be determined by Equations (4-5) as follows:

$$\text{In compression phase: } F_{d-c} = \begin{cases} \dfrac{2c_{s0}(\dot{x}_s - \dot{x}_u)}{\beta+1}, \text{ if } \alpha_c \le \dot{x}_s - \dot{x}_u < 0 \\ \dfrac{2c_{s0}}{\beta+1}\left[\alpha_c + \gamma_c\left(\dot{x}_s - \dot{x}_u - \alpha_c\right)\right], \text{if } \dot{x}_s - \dot{x}_u < \alpha_c \end{cases} \tag{4}$$

And,

$$\text{In rebound phase: } F_{d-r} = \begin{cases} \dfrac{2\beta c_{s0}(\dot{x}_s - \dot{x}_u)}{\beta+1}, \text{ if } 0 \le \dot{x}_s - \dot{x}_u < \alpha_r \\ \dfrac{2\beta c_{s0}}{\beta+1}\left[\alpha_r + \gamma_r\left(\dot{x}_s - \dot{x}_u - \alpha_r\right)\right], \text{ if } \dot{x}_s - \dot{x}_u \ge \alpha_r \end{cases} \tag{5}$$

where:

α_c, α_r : saturation factors.

γ_c, γ_r : high-speed damping reduction factors.

2.3. Transient road profile

Limiting speed may be important in certain zones, such as congested or accident-prone areas, residential streets, to encourage orderly traffic flow and reduced risk. And speed breakers or transient road bumps can be seen as an effective way to alert drivers to slow down the vehicle's velocity. These can have different shapes, heights and lengths depending on each country's traffic. In this paper, we use the two kinds of transient bumps which are applied in the two nations with the world greatest populations (China and India).

2.3.1. GB/T 4970-2009 standard

In the first case, the China's national standard GB/T 4970-2009 was employed to build the triangular bump model that simulates the dynamic responses of quarter car under transient excitation [15]. The formula for defining a bump's triangular profile is as follows [10]:

$$y = \begin{cases} \dfrac{2h}{L}vt; \text{ if } 0 \le t \le \dfrac{L}{2v} \\ 2h - \dfrac{2h}{L}vt; \text{ if } \dfrac{L}{2v} < t \le \dfrac{L}{v} \\ 0; \text{ if } \dfrac{L}{v} < t < +\infty \end{cases} \tag{6}$$

where, the specifications are shown as in Figure 3.

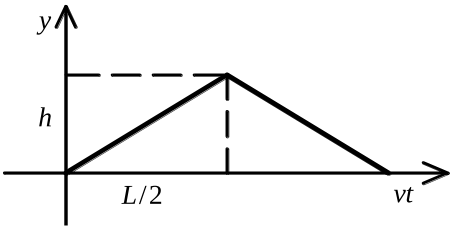


Figure 3. *A triangular bump model*

The triangular bump has a length of *L*=0.4(m) and a height of *h*=0.04(m) as described in standard GB/T 4970-2009 [15].

2.3.2. IRC-99-1988 standard

The Traffic Engineering Committee of the Indian Roads Congress has been considering on developing appropriate speed breakers which is a compromise design to suit average Indian road traffic conditions [16]. In the second case, the speed breakers may have different parameters depending on the type of vehicle and the function might be used to create transient road profile for bus with the following sine-squared shape:

$$y = \begin{cases} d_2 sin^2 \dfrac{\pi v}{d_1}; \text{ if } 0 \le t \le \dfrac{d_1}{v} \\ 0; \text{ if } t < 0, t > \dfrac{d_1}{v} \end{cases} \tag{7}$$

where, the specifications are shown as in Figure 4.

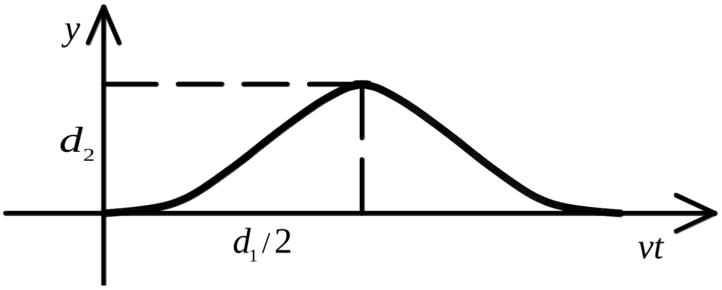


Figure 4. *A sine-squared bump model*

Generally, the sine-squared road surface has a length of d_1=3.7(m) and a height of d_2=0.1(m), as specified by standard IRC-99-1988 (m) [16].

3. Results and Discussions

At a bus's working velocity of 5-120(km/h), the research analyzes the impacts of a two-stage asymmetric damper on vibrational parameters, including the Maximum Body's Vibration Acceleration (MBVA), the Maximum Suspension Dynamic Deflection (MSDD), and the Maximum Tire Dynamic Load coefficient (MTDL). By using the maximum calculation, all the dynamic response values previously mentioned will be computed as follows [10]:

$$\text{MBVA} = \left|\ddot{x}_s(t)\right|_{\max} \tag{8}$$

$$\text{MTDL} = \left|\frac{k_t\left(x_u(t) - y(t)\right) + \text{c}_t\left(\dot{x}_u(t) - \dot{y}(t)\right)}{\left(m_s + m_u\right)g}\right|_{\max} \tag{9}$$

$$\text{MSDD} = \left|x_s(t) - x_u(t)\right|_{\max} \tag{10}$$

Here are the parameters used for the a typical two-stage asymmetric damper: $\gamma_c = 0.5$, $\gamma_r = 0.25$, $\alpha_c = -0.2$ (m/s), $\alpha_r = 0.1$ (m/s) which has been shown to provide an acceptable balance among the assessment criteria including suspension deflection, road-holding, and ride comfort under bump inputs [17]. In addition, $\beta = 70/30$ represents common asymmetric dampers in reality [18]. In another case, $\beta = 1$, $\gamma_c = \gamma_r = 1$ are damping characteristic determining a linear symmetric damper.

3.1. Triangular bump

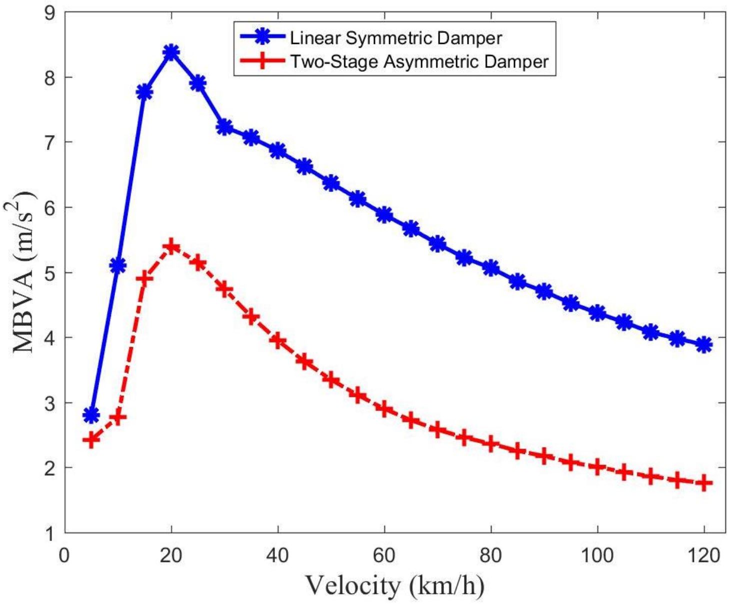


Figure 5. *MBVA versus velocity with two types of dampers under GB/T excitation*

At the beginning of a velocity's increment, the greater the velocity, the greater the MBVA. As illustrated in Figure 5, MBVA achieves peak values at around 20(km/h) and then steadily declines for both cases of dampers [10]. Over the entire working velocity range, the two-stage asymmetric damper offers a massively greater comfort level (approximately 55% at 100(km/h)) than the linear symmetric one.

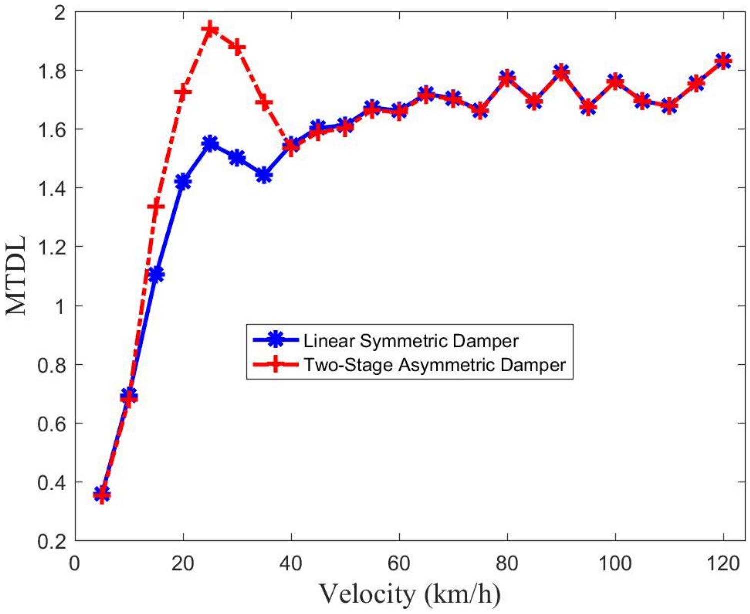


Figure 6. *MTDL versus velocity with two types of dampers under GB/T excitation*

The value of MTDL increases dramatically and reaches its peak value at around 25(km/h), then slightly declines [10] and maintains its value at about 1.6 in both cases, as shown in Figure 6. At lower part of velocity range (10<v_0<40(km/h)), the use of linear symmetric damper yields better handling control than the two-stage asymmetric one and the greatest difference is about 25% at 25(km/h). When the bus's velocity increase, the linear symmetric damper and the two-stage asymmetric one performs in the same way that there is no difference between them at v_0>40(km/h)).

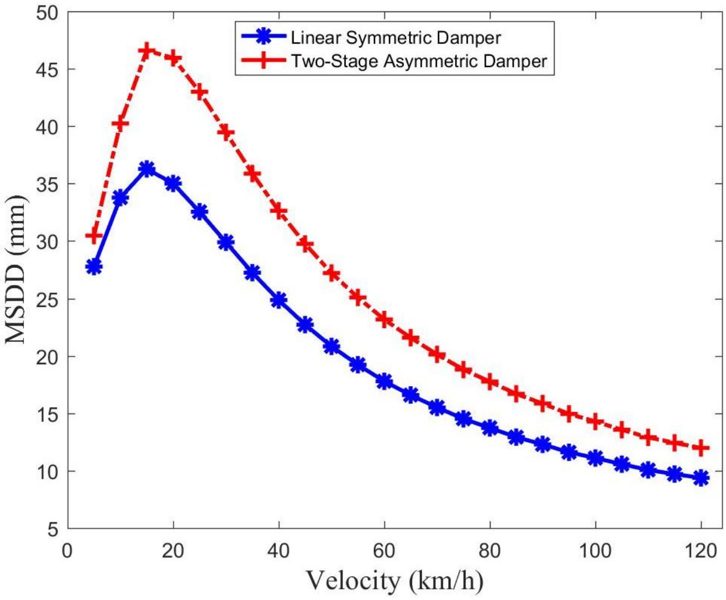


Figure 7. *MSDD versus velocity with two types of dampers under GB/T excitation*

For both damper cases, the MSDD reaches high values at around 15(km/h) before gradually declining as shown in Figure 7 [10]. It illustrates how the linear symmetric damper generates better working space throughout the entire velocity domain and biggest difference is around 32% at 25(km/h). However, the maximum amplitude of the MSSD is just 47(mm), which is much less than the restricted working space of the suspension. Hence, this criterion could be ignored in case of GB/T excitation.

3.2. Sine-squared bump

By applying the same algorithm and adjusting the input parameter from triangular bump to sine-squared bump, we get the results shown as below:

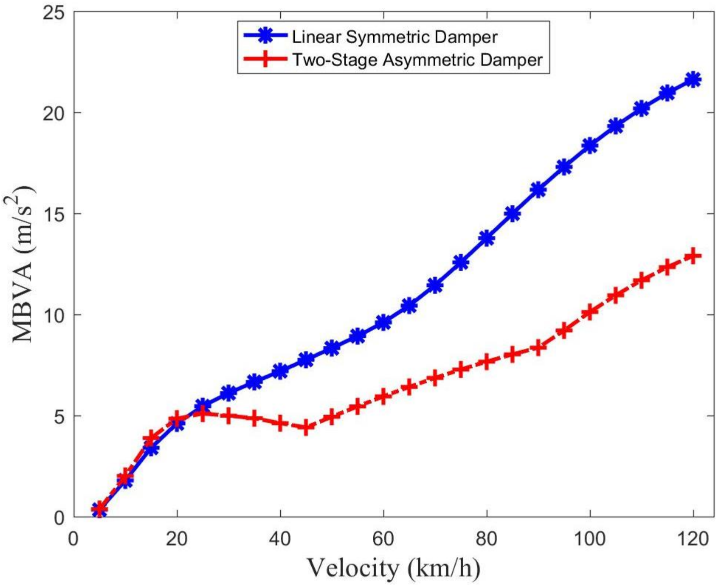


Figure 8. *MBVA versus velocity with two types of dampers under IRC excitation*

There is an increasing tendency in the entire velocity domain as shown in Figure 8. The graph illustrates how the two-stage asymmetric damper provides better performance on the MBVA in the velocity domain. Generally, the difference becomes more pronounced at the higher velocity and the biggest difference reaches 48% at 90(km/h).

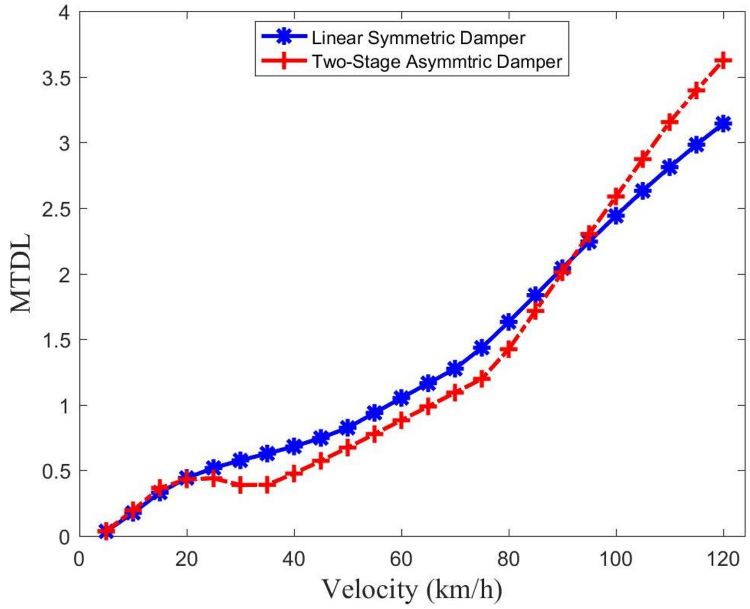


Figure 9. *MTDL versus velocity with two types of dampers under IRC excitation*

In terms of the MTDL evaluation index, the similar trend as MBVA index is observed. The two-stage asymmetric damper yields considerably better performance throughout most of the velocity domain and the highest variation is about 38% at 35(km/h), as shown in Figure 9. When the bus is running at high speed (v_0 >95(km/h)), the inverse trend is established, but it rarely happens due to the limited speed in crowded city.

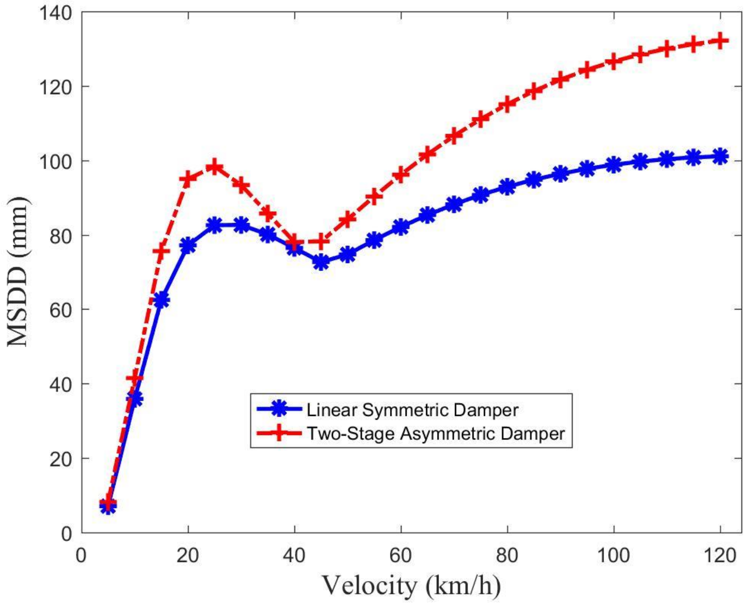


Figure 10. *MSDD versus velocity with two types of dampers under IRC excitation*

In the Figure 10, as the vehicle's speed rises, the amplitude of the MSDD becomes progressively bigger. Generally, the use of linear symmetric damper performs better in working space criteria at the entire working velocity range of an inner-city bus. As the velocity increases, the difference keeps growing up significantly and the highest difference reaches 31% at 120(km/h). One striking point is that the bus using the two-stage asymmetric damper will face to problems of limited working space at highway speed (the normal limitation of working space is 127(mm)) that may lead to severe structural damage.

4. Conclusions

The results of the analysis in this study enabled us to determine how a two-stage asymmetric damper would influence the vibrational behavior of an inner-city bus in the time domain under transient road profile. The research focused on the three evaluation indices of the inner-city bus model: Body Vibration Acceleration, Suspension Dynamic Deflection, and Tire Dynamic Load coefficient. The existence of asymmetric damper characteristics leads to the discovery of these following impacts:

1) The two-stage asymmetric damper performs greater performance in terms of ride comfort than the linear symmetric one in both cases of transient road profile.

2) In case of the triangular bump GB/T excitation, the linear symmetric damper will help to enhance handling control by reducing tire dynamic load at a regular working velocity in a populated city. In the event of the sine-squared bump IRC excitation, better performance is obtained by the two-stage asymmetric damper over majority of the velocity domain.

3) When an inner-city is subjected to a triangular bump, the working space criteria could be overlooked. However, when the vehicle is running at high speed and crossing over a sine-squared bump, a bus with a two-stage asymmetric damper might be at danger for serious structural failure due to lack of working space.

The primary contribution of this paper is the revelation of the two-stage asymmetric damper's influence rule on vertical characteristics. This paper also intends as a helpful guideline resource for enhancing handling and ride comfort under the road impact excitation. Further research should be conducted to determine the suspension's optimal nonlinear damping characteristic as an extension and continuation of this article.

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