Alternate Optimization of Speed Control Hump for Automobiles and Automobile Suspension*

(Reducing Excessive Shocks to Drivers of Heavy Vehicles by Multiobjective Optimization of Hump)

Ken-ichi MAEMORI** and Shinji ANDO***

In this paper, we propose an optimum design method of humps to reduce the excessive shocks experienced by drivers of heavy vehicles passing over existing circular arc humps with a length of 3.67 m at normal speeds, and to compensate for too few shocks experienced by drivers when light vehicles with semi-active suspensions pass over the same humps at excessive speeds. We take the standpoint of hump design and suspension design alternately, and determine the optimum dimensions of a circular arc hump by optimizing it and the damping coefficient of light vehicle suspension dampers alternately. The maximum acceleration of the driver of the heavy vehicle and that of the light vehicle is set as a multiobjective function for the optimization of the hump, while the maximum acceleration of the driver of the light vehicle is selected as a single objective function for the optimization of the suspension of it. It is found that the optimum hump determined in this study further reduces the excessive shock to drivers of heavy vehicles compared to the existing hump and to the optimum hump obtained in the previous study, in which heavy vehicles were not considered. For the light vehicles, a decrease in the amount of control of vehicle speed was found previously, but the present method is found to overcome this weak point. Speed control effects of the existing hump and the one optimized by the present method on three types of light vehicles with different wheelbases which have two types of conventional passive suspensions are compared using simulation calculations. The optimized hump exhibited less deviation among the above different vehicle types in terms of the speed control effects.

Key Words: Automobile, Transportation Engineering, Optimum Design, Multiobjective Optimization, ϵ -constant Method, Hump, Automobile Suspension, Damper, Transient Response

1. Introduction

Speed control humps are one means of reducing the speed of vehicles traveling faster than the designated limit. Drivers of vehicles should be warned using shocks experienced by the vehicles passing over humps when they are exceeding the speed limit. However, the shocks to the drivers should be as small as possible when the vehicles pass over the humps at

speeds less than or equal to the speed limit. In past reports⁽¹⁾⁻⁽⁸⁾, we studied the vehicle speed control effect of different sized humps, including existing ones^{(9),(10)} using computer simulations of various vehicles having conventional passive or semi-active suspension systems⁽¹¹⁾. We confirmed that an excessive amount of shock^{(9),(12),(13)} is experienced by drivers when heavy vehicles pass over these humps at speeds less than or equal to the speed limit. In addition, we found^{(7),(8)} that drivers of light vehicles having semi-active suspensions, which can adjust the damping forces relatively freely according to road conditions, thereby satisfying the requirements of ride quality and driving stability of vehicles, experienced too few shocks when the vehicles passing over these humps at

* Received 19th October, 1995.

** Faculty of Engineering, Kanagawa University, 3-27-1, Rokkakubashi, Kanagawa-ku, Yokohama 221, Japan

*** Graduate (M. C.), Kanagawa University, 3-27-1, Rokkakubashi, Kanagawa-ku, Yokohama 221, Japan

excessive speeds. We assumed that, in order to pass over the hump as quickly as possible, the driver's judgement in terms of satisfying the ride quality requirement is more important than that of driving stability, and that the damping forces are adjusted to match this requirement. From the standpoint of hump design, it is important to reduce the excessive amount of shock to drivers of heavy vehicles and to increase the too few shocks to drivers of light vehicles having semi-active suspensions when these vehicles passing over these humps.

In this report, we propose a multiobjective optimization method to reduce the amount of shock experienced by drivers when heavy vehicles pass over existing humps at normal speeds, and to increase the amount of shock experienced by drivers when light vehicles with semi-active suspensions pass over the same humps at excessive speeds. We adopt the ϵ -constant method⁽¹⁴⁾ and optimize the hump, by minimizing the maximum acceleration of the driver of heavy vehicles at the speed specified by hump design, and by maximizing the maximum acceleration of the driver of light vehicles at a speed higher than that used above setting an upper limit for the maximum acceleration of the driver at the speed specified by the hump design. In our previous report⁽⁸⁾, the shocks experienced by drivers of heavy vehicles were not considered in the optimization method of the hump, and the maximum acceleration of the driver of the heavy vehicles was not selected as an objective function.

In this report, we take the above standpoint of hump design and suspension design, which provides the best riding conditions for a wide range of vehicle speeds, alternately. Further, we optimize the dimensions of circular arc humps and the damping coefficients of semi-active suspension dampers of the light vehicle alternately. As an objective function in the suspension design, we set the maximum acceleration of the driver of the light vehicle at a speed faster than that specified by the hump design. This objective function is maximized for the optimization of the hump.

Furthermore, speed control effects of existing and optimized humps on three types of light vehicles with different wheelbases, including one with a semi-active suspension system, and one type of heavy vehicle are compared.

2. Nomenclature

- C : the damping coefficient
 C : the design variables, the damping coefficient of the damper
 $C_i (i=1, 2, 3, 4)$: the damping coefficient of the damper

- C_U, C_L : the upper and lower limits, respectively, of $C_i (i=1, 2, 3, 4)$
 $C_{opt,m}$: the m -th optimum solution of C
 F : the damping force of the damper or resisting force of the suspension spring
 F_{df}, F_{dr} : the damping force of the front and rear dampers, respectively
 H : the unit step function of Heaviside
 I_b : the inertia moment of the sprung mass around the center of gravity (c. g.)
 K : the spring constant
 L_f, L_r : the distances from the c. g. of the sprung mass to the front and rear axles, respectively
 L_o : the distance from the c. g. of the sprung mass to the c. g. of the driver
 L_{tf}, L_{tr} : the tire deflections for vehicles at rest
 L_w : the wheel base
 M : the mass
 P_K : the objective function transformed by the sequential unconstrained minimization technique (SUMT)
 p_K : the multiobjective function
 T : time
 X : the vertical displacement
 $\dot{X}_{df}, \dot{X}_{dr}$: the relative velocity of the front and rear damper, respectively
 $|\ddot{X}_o|_{\max}$: the maximum acceleration of the driver when the vehicle passes over the hump.
 $|\ddot{X}_o|_{\max,UH}$: the upper limit for $|\ddot{X}_{o,j}|_{\max}$ and $|\ddot{X}_{o,H,j}|_{\max}$ when the hump is optimized
 $|\ddot{X}_{o,H,j}|_{\max} (j=1, 2, \dots, J, J+1, J+2)$: the maximum acceleration of the driver of the heavy vehicle at $\dot{Z}_j$
 $(|\ddot{X}_{o,H,j}|_{\max})_0$: the value of $|\ddot{X}_{o,H,j}|_{\max}$ when the heavy vehicle passes over the existing hump
 $|\ddot{X}_{o,j}|_{\max} (j=1, 2, \dots, J, J+1, J+2)$: the maximum acceleration of the driver of the light vehicle at $\dot{Z}_j$
 $|\ddot{X}_{o,j}|_{\max,US} (j=J, J+2)$: the upper limit for $|\ddot{X}_{o,j}|_{\max}$ when the suspension is optimized
 $|\ddot{X}_{o,J+2}|_{\max,LH}$: the lower limit for $|\ddot{X}_{o,J+2}|_{\max}$ when the hump is optimized
 $|\ddot{X}_{o,j}|_{\max,UH} (j=J, J+2)$: the upper limit for $|\ddot{X}_{o,j}|_{\max}$ when the hump is optimized
 $(|\ddot{X}_{o,J+1}|_{\max})_{opt,m}$: the value of $|\ddot{X}_{o,J+1}|_{\max}$ when the light vehicle passes over the $Y_{opt,m-1}$ hump,
 $(|\ddot{X}_{o,J+1}|_{\max})_0$: the value of $|\ddot{X}_{o,J+1}|_{\max}$ when the light vehicle having the existing semi-active suspension dampers passes over the existing hump
 $X_{sfr}, X_{sfb}, X_{srr}, X_{srb}$: the deflections of springs $K_{sfr}, K_{sfb}, K_{srr}$ and K_{srb} , respectively
 X_{tf}, X_{tr} : the tire displacement on flat roads, assuming these values are zero for vehicles at rest

- Y : the design variables, the dimensions of the hump
 $Y_{n,U}, Y_{n,L}(n=1, 2)$: the upper and lower limit, respectively, for Y_n
 $Y_{opt,m}$: the m -th optimum solution of Y
 Z : the forward displacement of the c. g. of the sprung mass
 $\dot{Z}$: the speed of the vehicle passing over the hump
 $\dot{Z}_J$: the speed specified by the hump design
 $\dot{Z}_j(j=1, 2, \dots, J, J+1, J+2)$: the speed of the vehicle passing over the hump
 ϵ : the lower limit for $|\ddot{X}_{o,J+1}|_{\max}$ when the hump is optimized
 ϵ_X : positive number used to decide the convergence.
 θ_b : the angular displacement of the sprung mass during pitching
- Suffix
 b : the sprung mass
 df, dr : the front and rear dampers, respectively
 f, r : the front and rear unsprung masses, respectively
 o : the driver
 s : the seat
 sf, sr : the front and rear suspension springs, respectively
 tf, tr : the front and rear tires, respectively

3. Optimum Design Procedure

The ideal characteristics⁽⁹⁾ of humps are different from those of the suspension at a vehicle speed $\dot{Z}$ faster than $\dot{Z}_J$. Figure 1 shows the relationship between $\dot{Z}$ and $|\ddot{X}_o|_{\max}$ for a light and heavy vehicle,

Fig. 1 Relationship between maximum acceleration of the driver and traveling speed of the vehicle over the hump ($j=1, 2, \dots, J, J+1, J+2$)

respectively, passing over the same hump. In this optimum design, the above-mentioned ideal characteristics are examined in terms of the relationship between the maximum acceleration of the driver and the speed of the vehicle passing over the hump. The optimum hump size and suspension are studied to determine the ideal performance of these two. In the present paper, various parameters are expressed in nondimensional form⁽⁷⁾ introduced using the speed specified by the hump design and a wheelbase and mass of a vehicle.

3.1 Multiobjective optimization of the hump

In the first case, these vehicles are considered to pass over the hump at speeds less than or equal to $\dot{Z}_J$. In this case, the maximum acceleration of the drivers $|\ddot{X}_{o,H,j}|_{\max}$ and $|\ddot{X}_{o,j}|_{\max}(j=1, 2, \dots, J)$ should be as small as possible, so that we can minimize the objective function $|\ddot{X}_{o,H,J}|_{\max}$. $|\ddot{X}_{o,J}|_{\max}$ is confined by the upper limit $|\ddot{X}_{o,J}|_{\max,UH}$ as

$$|\ddot{X}_{o,J}|_{\max} - |\ddot{X}_{o,J}|_{\max,UH} \leq 0. \quad (1)$$

When the vehicle passes over the hump at a speed $\dot{Z}_{J+1}$, which is faster than $\dot{Z}_J$, the driver of the vehicle should be warned that he/she is exceeding the speed limit. Thus $|\ddot{X}_{o,J+1}|_{\max}$ is selected as the objective function which we try to maximize. Accordingly, to form a ϵ -constant problem, the lower limit ϵ is set as $|\ddot{X}_{o,J+1}|_{\max}$, and $|\ddot{X}_{o,H,J}|_{\max}$ is converted using the sequential unconstrained minimization technique (SUMT)⁽¹⁵⁾. Then we obtain the multiobjective function

$$p_K = |\ddot{X}_{o,H,J}|_{\max} + r_K(|\ddot{X}_{o,J+1}|_{\max} - \epsilon)^2 \times H(|\ddot{X}_{o,J+1}|_{\max} - \epsilon) \quad (K=1, 2, \dots), \quad (2)$$

where the second term on the right-hand side is a penalty function with a positive coefficient r_K , in which $r_{K+1} > r_K$.

By changing the value of ϵ , we obtain an optimum relationship between $|\ddot{X}_{o,H,J}|_{\max}$ and $|\ddot{X}_{o,J+1}|_{\max}$. This relationship is called a trade-off⁽¹⁶⁾.

The upper limit $|\ddot{X}_o|_{\max,UH}$ is set so that the vehicle can pass over the hump in safety. This condition is expressed as

$$\begin{aligned} |\ddot{X}_{o,H,J}|_{\max} - |\ddot{X}_o|_{\max,UH} &\leq 0 \\ |\ddot{X}_{o,j}|_{\max} - |\ddot{X}_o|_{\max,UH} &\leq 0 \\ (j=1, 2, \dots, J, J+1, J+2). \end{aligned} \quad (3)$$

When the speed of the light vehicle is $\dot{Z}_{J+2}$, which is faster than $\dot{Z}_{J+1}$, the maximum acceleration of the driver $|\ddot{X}_{o,J+2}|_{\max}$ is confined by both the lower limit $|\ddot{X}_{o,J+2}|_{\max,LH}$ and the upper limit $|\ddot{X}_{o,J+2}|_{\max,UH}$. That is,

$$|\ddot{X}_{o,J+2}|_{\max,LH} - |\ddot{X}_{o,J+2}|_{\max} \leq 0$$

and

$$|\ddot{X}_{o,J+2}|_{\max} - |\ddot{X}_{o,J+2}|_{\max,UH} \leq 0. \quad (4)$$

The dimensions of the cross section of the hump $Y=(Y_1, Y_2)^T$ are adopted as the design variables. We set the upper limit $Y_{n,U}$ and lower limit $Y_{n,L}$ for

the Y values as

$$Y_{n,L} - Y_n \leq 0, \quad Y_n - Y_{n,U} \leq 0 \quad (n=1, 2). \quad (5)$$

Constraint conditions (1) and (3)-(5) are expressed as

$$g_{hu}(Y) \leq 0 \quad (hu=1, 2, \dots, Hu). \quad (6)$$

By converting the multiobjective function p_K using SUMT, we obtain the objective function under a no-constraint condition as

$$P_K = p_K + r_K \left[\sum_{hu=1}^{Hu} \{g_{hu}(Y)\}^2 \times H\{-g_{hu}(Y)\} \right] \quad (K=1, 2, \dots). \quad (7)$$

3.2 Single objective optimization of suspension

The light vehicle having a semi-active suspension system is assumed to travel over the hump. Minimization of the maximum acceleration of the driver $|\ddot{X}_{o,J+1}|_{\max}$ at the speed $\dot{Z}_{J+1}$ is sought.

To optimize the suspension, the maximum acceleration of the driver at speeds $\dot{Z}_J$ and $\dot{Z}_{J+2}$, obtained in the preceding step, is set as the upper limits, $|\ddot{X}_{o,J}|_{\max,US}$ and $|\ddot{X}_{o,J+2}|_{\max,US}$, for the speed. Using three points, we reduce the maximum acceleration of the driver to below that attained during hump optimization, utilizing the above situation and minimization of $|\ddot{X}_{o,J+1}|_{\max}$. The above-mentioned constraint conditions are expressed by

$$\begin{aligned} |\ddot{X}_{o,J}|_{\max} - |\ddot{X}_{o,J}|_{\max,US} &\leq 0 \\ |\ddot{X}_{o,J+2}|_{\max} - |\ddot{X}_{o,J+2}|_{\max,US} &\leq 0. \end{aligned} \quad (8)$$

As a design variable, the damping coefficient of damper $C=(C_1, C_2, C_3, C_4)^T$ is adopted. By expressing the damping force of the front and rear dampers as F_{df} and F_{dr} , respectively, and the relative velocity of the front and rear dampers as $\dot{X}_{df}$ and $\dot{X}_{dr}$, respectively, we obtain

$$\begin{aligned} F_{df} &= C_1 \dot{X}_{df} \quad (\dot{X}_{df} \leq 0) \\ &= C_2 \dot{X}_{df} \quad (\dot{X}_{df} > 0), \\ F_{dr} &= C_3 \dot{X}_{dr} \quad (\dot{X}_{dr} \leq 0) \\ &= C_4 \dot{X}_{dr} \quad (\dot{X}_{dr} > 0). \end{aligned} \quad (9)$$

The constraint conditions for C are

$$\begin{aligned} C_L - C_i &\leq 0, \quad C_i - C_U \leq 0, \\ (i=1, 2, 3, 4), \quad C_2 - C_1 &\leq 0, \\ C_4 - C_3 &\leq 0, \quad C_3 - C_1 \leq 0, \quad C_4 - C_2 \leq 0. \end{aligned} \quad (10)$$

By expressing the constraint condition formulas (8) and (10) as

$$g_{su}(C) \leq 0 \quad (su=1, 2, \dots, Su) \quad (11)$$

and converting $|\ddot{X}_{o,J+1}|_{\max}$ by SUMT, a single objective function under a no-constraint condition is obtained

$$P_K = |\ddot{X}_{o,J+1}|_{\max} + r_K \left[\sum_{su=1}^{Su} \{g_{su}(C)\}^2 \times H\{-g_{su}(C)\} \right] \quad (K=1, 2, \dots). \quad (12)$$

3.3 Alternate optimization of the hump and suspension

A macro-flow chart for alternate optimization is shown in Fig. 2. The above-mentioned procedures

Fig. 2 Macro-flow chart for alternate optimization

(sections 3.1 and 3.2) are alternately repeated until convergence is obtained.

4. Example of Design

When the driver of the $L_w=1$ vehicle with a semi-active suspension system described in Table 1 (Fig. 3) anticipates traveling over a circular arc hump, it is assumed that the driver adjusts the damping forces automatically or manually so that the vehicle may travel over the hump as quickly as possible. In this case, alternate optimization is carried out using three vehicle speeds, i.e., $\dot{Z}_1=1$, $\dot{Z}_2=1.5$, and $\dot{Z}_3=2$, where $\dot{Z}_1$ is the designated traveling speed over the humps. The constraint conditions were $C_L=0$, and $C_U=5$ for the optimization of the suspension, and $Y_{1,L}=1$, $Y_{1,U}=5$, $Y_{2,L}=0.01$, $Y_{2,U}=0.04$, $|\ddot{X}_{o,1}|_{\max,UH}=0.17$, $|\ddot{X}_{o,3}|_{\max,LH}=0.25$, $|\ddot{X}_{o,3}|_{\max,UH}=0.5$, $|\ddot{X}_o|_{\max,UH}=2.5$, and $\epsilon=0.15-0.25$ for the optimization of the hump.

The following equations of motion were adopted for the simulation calculations.

$$\begin{aligned} M_o \ddot{X}_o &= -K_s \{X_o - (X_b + L_o \theta_b)\} \\ &\quad - C_s \{\dot{X}_o - (\dot{X}_b + L_o \dot{\theta}_b)\} \\ M_b \ddot{X}_b &= -K_s \{(X_b + L_o \theta_b) - X_o\} \\ &\quad - C_s \{(\dot{X}_b + L_o \dot{\theta}_b) - \dot{X}_o\} + F_{sf} + F_{sr} + F_{df} + F_{dr} \\ M_f \ddot{X}_f &= K_{tf}(X_{tf} - X_f) - F_{sf} - F_{df} \\ M_r \ddot{X}_r &= K_{tr}(X_{tr} - X_r) - F_{sr} - F_{dr} \\ I_b \ddot{\theta}_b &= -K_s L_o \{(X_b + L_o \theta_b) - X_o\} \\ &\quad - C_s L_o \{(\dot{X}_b + L_o \dot{\theta}_b) - \dot{X}_o\} \\ &\quad + L_f (F_{sf} + F_{df}) - L_r (F_{sr} + F_{dr}) \\ F_{sf} &= K_{sf} X_{sf} + K_{sfr} X_{sfr} + K_{sfb} X_{sfb} \\ F_{sr} &= K_{sr} X_{sr} + K_{srr} X_{srr} + K_{srb} X_{srb} \\ X_{sf} &= X_{df} = X_f - (X_b + L_f \theta_b) \\ X_{sr} &= X_{dr} = X_r - (X_b - L_r \theta_b) \end{aligned} \quad (13)$$

Table 1 Specifications of dynamic model for automobiles

L_w	M_o	M_b	M_r	M_f	I_b	C_s
1	0.1	0.85	0.075	0.075	0.25	0.55
1.7	0.1	10	1	1	7.5	0.55
L_w	K_s	K_{sf}	K_{sr}	K_{sfr}	K_{sfb}	
1	7	5.5	6	100	2.2×10^5	
1.7	7	250	250	2500	1.5×10^9	
L_w	K_{srr}	K_{srb}	K_{tf}	K_{tr}	L_f	L_o
1	100	2.2×10^5	60	60	0.5	-0.1
1.7	2500	1.5×10^9	400	400	0.85	1.1

Fig. 3 Dynamic model of suspension system for automobiles and cross-sectional profile of the circular arc hump

$$\begin{aligned}\dot{X}_{df} &= \dot{X}_f - (\dot{X}_b + L_r \dot{\theta}_b), \quad \dot{X}_{dr} = \dot{X}_r - (\dot{X}_b - L_r \dot{\theta}_b) \\ X_{tf} &= \sqrt{-(Z + Y_1/2)^2 + R^2} - Y_1^2/(8Y_2) + Y_2/2 \\ X_{tr} &= \sqrt{-\{(Z - L_w) + Y_1/2\}^2 + R^2} - Y_1^2/(8Y_2) + Y_2/2 \\ R &= Y_1^2/(8Y_2) + Y_2/2, \quad Z = \dot{Z}T\end{aligned}$$

When the tires are not in contact with the hump or the road, the following calculation is used

$$X_{tf} = X_f - L_{tf}, \quad X_{tr} = X_r - L_{tr}. \quad (14)$$

Figure 4 shows the optimal relationship between the objective functions $|\dot{X}_{o,H,1}|_{\max}$ and $|\dot{X}_{o,2}|_{\max}$ in the case of hump optimization when $m=1$ and 2. It also shows convergence for each optimal point A, B, C, D, E, F in the alternate optimization in which the starting point is A and the convergence point is F (at this point $C = C_{opt,3}$ obtained on the condition that $Y = Y_{opt,2}$). The points C and E are the preferred solutions because $|\dot{X}_{o,2}|_{\max} = (|\dot{X}_{o,2}|_{\max})_0$ and $|\dot{X}_{o,H,1}|_{\max} < (|\dot{X}_{o,H,1}|_{\max})_0$. The point F is almost equal to the point E ($Y = Y_{opt,2}$, obtained assuming that $C = C_{opt,2}$).

Figure 5 shows the results of the simulation calculations using the optimized hump dimensions and damping forces of the dampers. The solid line ($L_w =$

Fig. 4 Pareto optimal solutions and conditions for convergence for alternate optimization of the suspension and the hump

Fig. 5 Effect of alternate optimization of the suspension and the hump in terms of vehicle speed control effect

1, existing suspension and hump) shows the results when a light vehicle with a semi-active suspension system whose dampers are adjusted to the existing "soft" (17) damping force characteristics travels over

the existing circular arc hump⁽¹³⁾. The alternating long and short dashed line ($L_w=1.7$, existing hump) shows the results when the heavy vehicle travels over the existing circular arc hump. In this case, the driver of the heavy vehicle experiences an excessive amount of shock compared to that of the light vehicle.

The dotted line ($L_w=1$, $C_{opt,1}$) shows the results when the maximum acceleration of the driver at $\dot{Z}=1.5$ is minimized by adopting the upper limit values $|\ddot{X}_{o,1}|_{\max,US}$ and $|\ddot{X}_{o,3}|_{\max,US}$ for the maximum acceleration of driver at $\dot{Z}=1$ and $\dot{Z}=2$, respectively. This is the condition under which the damping force is optimized for the existing circular arc hump. The speed control effect of the existing hump on the light vehicle is generally reduced, as seen in the lowering of the maximum acceleration of the driver over a wide range, compared with the previously mentioned "soft" characteristics.

The $Y_{opt,1}$ hump was developed to minimize the maximum acceleration of the driver of the heavy vehicle at $\dot{Z}=1$ and to maximize the maximum acceleration of the driver of the light vehicle at $\dot{Z}=1.5$ for this optimized suspension $C_{opt,1}$. In this case, the maximum acceleration of the driver of the light vehi-

cle ($L_w=1$, $Y_{opt,1}$) was faster than or equal to the above-mentioned two cases at $\dot{Z}=1.5$, but that of the heavy vehicle ($L_w=1.7$, $Y_{opt,1}$) was lower over the entire range compared with the existing hump.

The alternating long and short dashed line ($L_w=1$, $C_{opt,3}$) shows the results when C is optimized for the optimum solution $Y_{opt,2}$ obtained in the preceding step. This curve ($L_w=1$, $C_{opt,3}$) is almost identical to the $Y_{opt,2}$ curve (not shown) and satisfies the conditions of convergence for the maximum acceleration of the driver of the light vehicle at $\dot{Z}=1.5$. For this $Y_{opt,2}$ hump, the maximum acceleration of the driver of the heavy vehicle ($L_w=1.7$, $Y_{opt,2}$) is lower throughout the entire range of the vehicle speeds, and is reduced 24.7% and 8.8% at $\dot{Z}=0.5$ and 1, respectively, for the existing hump, and 60.9% and 54.2% at $\dot{Z}=0.5$ and 1, respectively, for the optimum hump (see Fig. 6(b), $L_w=1.7$, obtained by the method used in a previous report⁽⁸⁾) obtained in a previous study⁽⁸⁾ in which the maximum acceleration of the driver of the heavy vehicle was not used as an objective function.

From these results, we can confirm that the optimum hump is $Y_{opt,2}=(2.475, 0.03992)^T$ and the optimum suspension is $C_{opt,3}=(2.539, 1.205, 1.621, 1.205)^T$.

(a) Existing hump

(b) Optimized hump $Y_{opt,2}$

Fig. 6 Comparison of vehicle speed control effect on four vehicle types

The length and height of the existing hump expressed in nondimensional form with a wheelbase of 2.52 m are $Y=(1.452, 0.02976)^T$.

Figure 6 shows a comparison of the speed control effect of the existing and optimized humps, using the four types of vehicles shown in Table 1, including the vehicles with $L_w=0.85$ and $L_w=1.15$ having conventional passive suspension systems. The optimized hump shows less deviation among the light vehicle types in terms of the speed control effect, and the effectiveness of this hump is confirmed.

5. Conclusion

Cross-sectional dimensions of a hump and the damping coefficients of dampers of a light vehicle with a semi-active suspension system were optimized alternately for light and heavy vehicles traveling over a circular arc hump. For the optimization of the hump, the maximum acceleration of the driver of the heavy vehicles at the recommended speed for the hump, and that of the light vehicle at 1.5 times the recommended speed were selected as the multiobjective function. For the optimization of the dampers, the maximum acceleration of the driver at 1.5 times the recommended speed for the hump was selected as the single objective function. These two objective functions were used, alternately, to determine the optimum values. The results obtained are summarized as follows:

(1) In the multiobjective optimization of the hump, a set of Pareto optimal solutions for the two objective functions was obtained and a trade-off relationship was discovered.

(2) The optimized hump reduced the excessive amount of shock experienced by the driver when heavy vehicles travel over the existing hump at less than or equal to the recommended speed.

(3) The optimized hump reduced the excessive amount of shock experienced by the driver when heavy vehicles travel over the optimum hump obtained in a previous study; in that study, for shocks occurring in heavy vehicles the optimization method of the hump at speeds less than or equal to the recommended one, were not taken into account.

(4) For light vehicles with a semi-active suspension system involving optimum dampers, a decrease in the amount of control of vehicle speed was found previously, but optimizing the hump compensated for this weak point.

(5) Speed control effects of both existing and optimized humps on three types of light vehicles with different wheelbases and two types of conventional passive suspension systems were compared using simulation calculations. The optimized hump caused less

deviation of the speed control effect than the existing one for the three different vehicle types.

Acknowledgment

The authors are very grateful to Mr. Susumu Kumakura, research associate, Department of Mechanical Engineering, Kanagawa University, for his assistance during this investigation.

References

- (1) Maemori, K. and Sakamoto, K., Optimum Design of Speed Control Humps for Vehicles, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 54, No. 502, C (1988), p. 1217.
- (2) Maemori, K., Optimum Design of Speed Control Humps for Vehicles (A Method Optimizing a Hump in a Lump for Various Vehicles with Different Wheelbases), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 55, No. 515, C (1989), p. 1660.
- (3) Maemori, K., Multiobjective Optimum Design of Circular Humps for Vehicles, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 56, No. 525, C (1990), p. 1238.
- (4) Maemori, K., Multiobjective Optimum Design of Circular Humps for Vehicles (Using Weighted Tchebycheff Norm Method for Humps with Ease-ment Curves), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 57, No. 535, C (1991), p. 795.
- (5) Sakamoto, K. and Maemori, K., Influence of Elasticity of a Hump on Speed Control for Vehicles, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 57, No. 536, C (1991), p. 1170.
- (6) Maemori, K. and Sakamoto K., Multiobjective Optimum Design of Circular Humps for Vehicles (In the Case of Humps with Elasticity), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 58, No. 548, C (1992), p. 1054.
- (7) Maemori, K. and Ando, S., Alternate Optimization between a Speed Control Hump for Automobiles and Automobile Suspensions, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 576, C (1994), p. 2791.
- (8) Maemori, K., Alternate Optimization of Speed Control Hump for Automobiles and Automobile Suspension (Minimization of Each Single objective function), *JSME Int. J., Ser. C*, Vol. 38, No. 3 (1995), p. 552.
- (9) Watts, G. R., Road Humps for the Control of Vehicle Speed, *TRRL Rep. LR-597* (1973), Transport and Road Research Laboratory.
- (10) Baguley, C., Speed Control Humps-Further Public Road Trials, *TRRL Rep., LR-1017* (1981), Transport and Road Research Laboratory.
- (11) Tanaka, T., Morita, T., Togashi, A., Yoshida, Y. and Kishimoto, N., Preview Control to ECS, *J. Soc. Auto. Eng. Jpn.*, (in Japanese), Vol. 46, No. 3 (1992), p. 46.
- (12) Clement, J. P., Speed Humps and Thousand Oaks

- Experience, ITE J., Vol. 53, No. 1 (1983), p. 35.
- (13) Stephens, B., W., Road Humps for the Control of Vehicular Speeds and Traffic Flow, Public Road, Vol. 50, No. 3 (1986), p. 82.
- (14) Sakawa, M., Optimization of Nonlinear Systems (in Japanese), (1987), p. 120, Morikita Shuppan.
- (15) Kowalik, J. and Osborne, M.R., (Translated by Yamamoto, Y., and Koyama, T.), Methods for Unconstrained Optimization Problems (in Japanese), (1975), p. 109, Baifukan.
- (16) Sakawa, M., Optimization of Nonlinear Systems (in Japanese), (1987), p. 119, Morikita Shuppan.
- (17) Takagi, K., Yamaoka, S., Yamaguchi, Y. and Enoki, T., J. Soc. Auto. Eng. Jpn., (in Japanese), Vol. 37, No. 11 (1983), p. 1283.
-