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Using HVE to Study Vehicle Dynamics: An Example

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Abstract

In this paper we examine some handling metrics of vehicles equipped with space-saver tires and compare the metrics with performance of the vehicles on standard OEM tires using vehicle data available in HVE/SIMON. Vehicle data for 162 vehicles contained in the HVE vehicle data base was used and various linear handling characteristics were calculated for each vehicle. Tire performance data for representative space-saver tires were developed on a well-known and validated tire test machine and understeer gradient and initial step steer behavior showed that space-saver tires are reasonably capable substitutes for OEM tires under many linear handling conditions.

Introduction

Many modern vehicles utilize so-called “space-saver” spare tires. Such tires are usually not fitted to the vehicle and driven on until a problem has arisen with a service tire, and are limited in the mileage and speeds at which they can operate. They also may have some different characteristics (rolling radius, tread pattern, contact patch width and length, aspect ratio, stiffnesses, self-aligning torques, etc.) than the service tires with which the vehicle is equipped. As such, they have the potential for altering the handling signature of a vehicle when they are fitted. The author previously was able to test two different space-saver spare tires using the T.I.R.F. (Tire Industry Research Facility) machine at Calspan Corporation, 4455 Genesee Street, Buffalo, NY, 14225 USA [1,2]. That machine is shown in Figure 1.

The two space-saver tires tested were different in mechanical construction and configuration and are shown in Figures 2 and 3:

Figure 1: Calspan T.I.R.F. test machine

Figure 2: Goodyear T125/70-D14 space-saver spare tire

Figure 3: Vredestein 165/70-16 space-saver spare tire

To obtain vehicle and tire data needed for handling analyses, the HVE vehicle database was employed [3]. A total of 162 passenger cars from this database were examined to determine the potential effect of a space-saver spare tire on vehicle dynamics and handling. From [3], the following data were recorded: curb weight, fore/aft center of gravity location, tire cornering stiffness coefficient values, tire size and properties, and as-built vehicle understeer gradient.

The HVE database contains vehicle and tire metrics for a large variety of vehicles. It is important to recognize that the tire properties included in the HVE database are *representative* of tires having the correct OEM size for each vehicle, but the properties are generic tires in the sense that no *specific* tire manufacturers are listed there. Generic data for the tires contained in the database were obtained by actual testing of various individual/manufacturer tires [1,2].

Tire cornering stiffness coefficient values necessary for handling analyses were measured at three different vertical loads during the T.I.R.F. tire testing program. In calculating the individual vehicle understeer gradient (UG) for each vehicle through use of the cornering stiffness coefficient value, it was usually the case that the *actual* F_z vertical load for each tire was *not* one of the vertical loads measured during tire testing program. In this analysis, cornering stiffness values for the as-built vertical loads for each vehicle tire position were developed by linearly interpolating between load values. An example of the salient vehicle and tire data necessary for low-a_y linear handling analyses is given for a 2004-2013 Buick LaCrosse passenger car in Table 1 [3].

Table 1: 2004-2013 Buick LaCrosse data, HVE database

vehicle type:	Buick LaCrosse
OEM tire size:	P245/50-R17 (generic tire)
wheelbase:	111.76 in 283.87 cm
unladed weight:	3,911 lb_f/17 396.13 N
yaw inertia:	30,963.09 in-lb_f-sec^2 3764.48 kg-m^2
front tire F_z:	1,164.88 lb_f 5,181.39 N
rear tire F_z:	790.84 lb_f 3,517.66 N

Tire data obtained from the HVE database for the P245/50-R17 *generic* tires specified as OEM-size for this vehicle are shown in Figure 4 below for the tire test load of 992 lb_f/4412 N [3]:

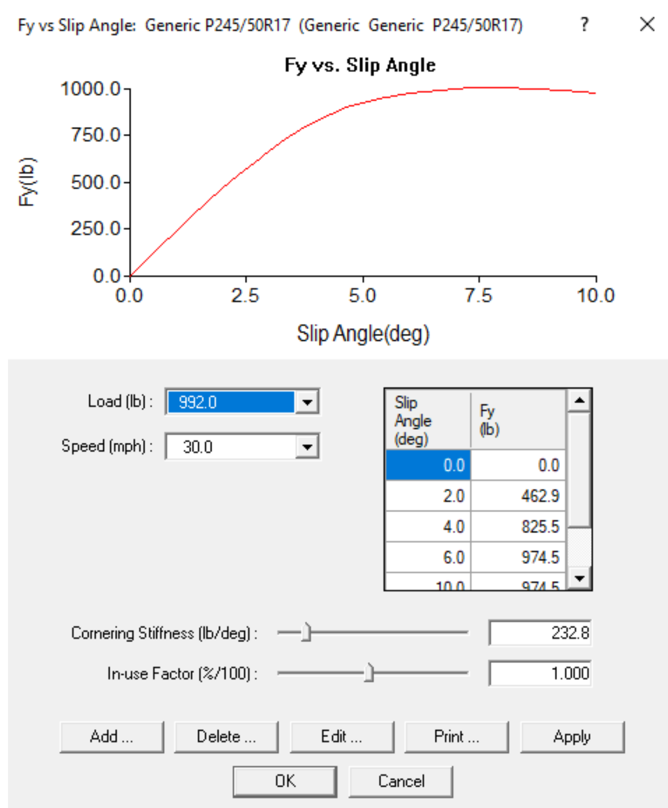

Figure 4: HVE screen shot showing tire properties for the 2004-2013 Buick LaCrosse tires

The three different vertical loads tested (only the first is shown above in Figure 4), resulting in three values for the cornering stiffness coefficient for each corresponding load, are shown in Table 2

Table 2: Tire vertical loads and associated cornering stiffness coefficients, 2004-2013 Buick Lacrosse P245/50-=R17 generic tire

tire test load, F_z	tire cornering stiffness
992 lb_f/4412 N	232.8 lb_f/deg 1,035 N/deg
1,984 lb_f/8,825 N	334.5 lb_f/deg 1,488 N/deg
2,976 lb_f/13,246 N	384.0 lb_f/deg 1,708 N/deg

At the curb weight and weight distribution of this exemplar Buick LaCrosse vehicle, the front and rear tire interpolated cornering stiffness coefficients for the OEM generic tires become:

front:	250.5 lb_f/deg	
	1,114 N/deg	
rear:	212.2 lb_f/deg	
	944N/deg	

CALCULATIONS

VEHICLE UNDERSTEER GRADIENT: Vehicle understeer gradient (UG) is a linear handling computational concept useful in the range $a_y \in [\mp\sim 0.3 - 0.4g]$ and is defined by [4-6]:

$$UG\left(\frac{deg}{g}\right) = 57.3\left\{\frac{W}{\ell}\right\}\left\{\frac{a}{C_R} - \frac{b}{C_F}\right\} \equiv \frac{W_F}{C_{LF}+C_{RF}} - \frac{W_R}{C_{LR}+C_{RR}} \qquad (1)$$

In Eq (1), the C_i are the front and rear cornering stiffness coefficients (Σ of left and right tire) in the 2-degree of freedom bicycle model and represent the slope of the slip angle v. sideforce curve at α=0, *i.e.:*

$$C_i = \frac{\partial F_Y}{\partial \alpha} \; @\alpha = 0^o \qquad (2)$$

It is straightforward to calculate the UG for a vehicle equipped with OEM tires; only the data from [3] as shown by example in Table 1 are required, along with the linearly-interpolated values for the individual C_i-values. In HVE, UG is directly available for each vehicle model in the HVE database by clicking on the vehicle c.g. and selecting the handling tab in the pulldown menu, as shown in Figure 5:

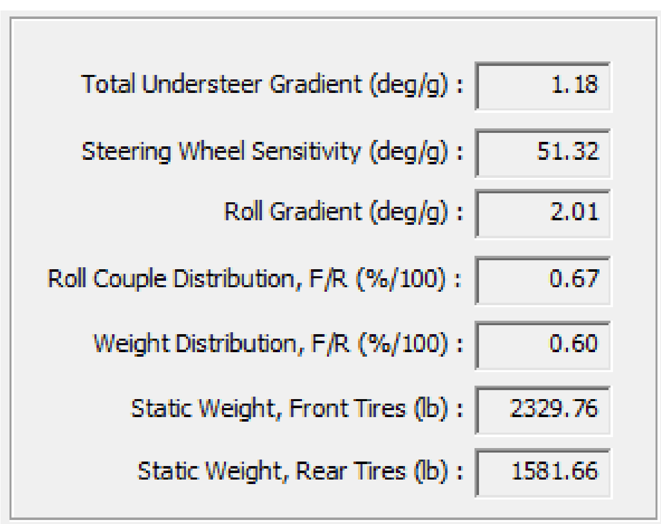

Figure 5: HVE screen shot showing handling data for 2004-2013 Buick LaCrosse vehicle

INITIAL YAW AND SIDESLIP ACCELERATIONS: From the equations of motion for the 2-degree of freedom bicycle model, the initial or “turn in” sideslip acceleration and yaw acceleration, normalized per unit of step steer input δ for each vehicle, are given by [3,4]. At t=0+, sideslip acceleration and yaw acceleration are 0 so:

$$\frac{\dot{v}}{\delta} @t = 0^+ = \frac{-C_f}{m} \qquad (3)$$

$$\frac{\dot{r}}{\delta} @t = 0^+ = \frac{-aC_f}{I_{zz}} \qquad (4)$$

In Eqs (3,4) a linearly-interpolated value for C_f was again employed for each vehicle.

STEADY-STATE YAW RATE AND SIDESLIP VELOCITY: With a step-steer input, the vehicle will eventually traverse a circular path (assuming it has a positive UG) once transients have died out (*i.e.*, as $t \rightarrow \infty$). The normalized steady-state yaw rate and sideslip velocity per unit of step steer input δ are given by:

$$\frac{r}{\delta} = \frac{u\ell C_f C_r}{mu^2(aC_f - bC_r) + \ell^2 C_f C_r} \qquad (5)$$

$$\frac{v}{\delta} = \frac{u(aC_f mu^2 + b\ell C_f C_r)}{mu^2(aC_f - bC_r) + \ell^2 C_f C_r} \qquad (6)$$

From Eqs (5,6) the following observations can be made:

1. both r and v are normalized per unit δ of step-steer input
2. forward velocity u nonlinearly scales the value of r and v
3. the denominators of both equations are, as expected, equal

Eqs (1,3-6) can be used as metrics to compare linear vehicle behavior with and without a space-saver tire mounted on one axle (front or rear) and/or on inside or outside position. Numerical calculations using Eqs (5,6), however, require an assumed forward velocity u-value.

EFFECT OF A SPACE-SAVER TIRE: Space-saver spare tire cornering stiffness coefficient data for two representative space-saver spare tires are given in [2] and are summarized in Table 3. Due to availability, financial and time constraints, only two space-saver tires were able to be tested. While the data thus obtained are both useful and likely representative of other space-saver tires, results might be improved if data for the actual space-saver tires fitted to each vehicle under consideration were available.

Table 3: Space-saver tire data (source: [2])

tire test load, F_z	tire cornering stiffness
	Goodyear T125/70-D14 tire
600 lb_f/2,669 N	152 lb_f/deg or 676 N/deg
950 lb_f/4,226 N	187 lb_f/deg or 832 N/deg
1,300 lb_f/5,782 N	195 lb_f/deg or 887 N/deg
	Vredestein 165/70-16 tire
600 lb_f/2,669 N	228 lb_f/deg or 1,014 N/deg
950 lb_f/4,226 N	225 lb_f/deg or 1,001 N/deg
1,300 lb_f/5,782 N	203 lb_f/deg or 903 N/deg

From Table 3, the following observations can be made:

1. The Goodyear T125/70-D14 tire had a cornering stiffness coefficient which monotonically *increased* throughout the range of vertical loads applied to the tire. At the highest measured F_z-value of 1,300 $lb_{f/}$, the tire cornering stiffness coefficient had *increased* by 28% while vertical load had increased 117%. The Vredestein 165/70-16 tire reversed this trend at the highest test load.
2. The cornering stiffness coefficient values are of the same order of magnitude as the cornering stiffnesses of the standard tires that they replaced, and in some cases are actually larger! It is logical to suspect that changes in vehicle behavior occurring because a space-saver tire has been mounted may at times be minimal, depending on vehicle, tire combination & maneuver/weight transfer.

As Figure 3 shows, the Vredestein 165/70-16 tire is of an unusual, expanding construction and configuration, and not typical of the space-saver tires installed in most passenger cars (it was the OEM space-saver tire for a Porsche 993 sports car). For the calculated results which follow therefore, the Goodyear T125/70-D14 tire data were used exclusively and were considered *representative* of space-saver tire performance and characteristics. In order to investigate the effect of installing a space-saver tire, either one front or one rear tire must have the space-saver tire stiffness coefficient, again interpolated for the actual corner weight of the vehicle.

RESULTS

Table 4 shows the maximum, minimum, average and standard deviation values for the tire stiffnesses, weight distribution, yaw moment of inertia and UG-values for the 162 vehicles examined. All tire stiffness values were interpolated to stock corner vertical loads (*i.e.,* no payloads were considered), as noted in the Introduction. Units are given at the end of the paper. As expected from Eqs (3,4) initial sideslip acceleration and yaw acceleration are only dependent on inertias, distance a from c.g. to front axle and front tire cornering stiffness coefficients.

Table 4: Summary of results and data for all 162 HVE database vehicles

Property	Max	Min	Avg	St. Dev.
C_F	330.63	84.78	189.62	60.73
C_R	282.97	71.48	151.17	50.06
W_F	1339.98	428.14	925.12	164.70
W_R	1045.45	325.75	637.21	161.56
W_T	4571.11	1705.96	3126.47	592.10
I_{zz}	36951.65	12708.47	23749.0	5870.36
UG_{STOCK}	2.47	-1.01	0.81	0.69
UG_{FTMOD}	2.39	-1.46	0.65	0.56
UG_{RTMOD}	3.43	-0.63	1.04	1.06
$\dot{v}/\delta_{OEM\ tire}$	5.99	2.45	3.86	0.84
$\dot{v}/\delta_{front\ space-saver}$	4.89	2.76	3.85	0.44
$\dot{r}_{/\delta OEM\ tire}$	1.25	0.36	0.67	0.20
$\dot{r}/\delta_{front\ space-saver}$	0.20	0.07	0.12	0.03

0.12 0.03

Some values for outlying/unusual individual vehicle/tire combinations are shown in Table 5:

Table 5: Values for outlier vehicle/tire combinations

Largest stock UG (2.47)	Oldsmobile delta 88
Smallest stock UG (-1.01)	VW Beetle/Type 1
Largest UG/front space-saver (2.39)	Oldsmobile Alero
Smallest UG/front space-saver (-1.46)	VW Beetle/Type 1
Largest UG/rear space-saver (3.43)	VW Rabbit
Smallest UG/rear space-saver (-0.63)	Mercedes-Benz S420

DISCUSSION

The results of the calculations performed show the following trends and allow some generalizations to be drawn:

1. It is obvious from Eq (1) that increasing a and/or C_F *generally* leads to a decreased UG, and conversely, increasing b and/or C_R *generally* leads to an increased UG. However, for some vehicles, replacing an OEM tire with a space-saver tire produced essentially *no* change in UG. This occurred because the representative space-save tire used had about the same cornering stiffness coefficient as the tire it replaced, both operating at the actual/interpolated vertical tire load.

2. As noted above, results might be different if the space-save tire *actually* supplied with each vehicle replaced the generic Goodyear T125/70-D14 used for the calculations. This would require testing of each tire. There might also be a small improvement in realism if the interpolation procedure used to compute cornering stiffness coefficients on the basis of actual F_z-values was quadratic instead of linear. Curves of cornering stiffness coefficient vs. F_z almost never exhibit a point of inflection & always increase monotonically, so a quadratic fit would be sufficiently rich.

3. It is unnecessary to calculate values for $\dot{v}/_{rear\ space-saver}$ and/or $\dot{r}_{rear\ space\ saver}$ because the initial values for these variables are unaffected by changes in rear tire cornering stiffness coefficients; see Eqs (3,4)

4. For the simple two-degree-of-freedom bicycle model, slip angles/g are the cornering compliances. *Effective* slip angles/g differ for a more complex real vehicle model (*e.g.,* SIMON, CARSIM*, etc.)*. For either an Olley applied force test or for a steered path test (either constant radius or constant speed) the *cornering compliances* determine the steer characteristics of the vehicle. A virtue of the cornering compliance concept is that the various effects which contribute to handling may be evaluated separately and summed. The difference between the front and rear Bundorf cornering compliances can be summed to give a numerical measure of under/oversteer in degrees/g, as before, referred to as the vehicle understeer gradient (UG). Summing the separate effects of tire/weight, roll steer, camber, deflection, aligning torque steer, *etc.*, is termed the vehicle *understeer budget* (UB). An example of an UB is given in Table 6 [8]. As expected, tire cornering stiffness values and compliances dominate the UB.

	Front D_F, deg./g	Rear D_R, deg./g
Weight distribution effect, i.e., tire cornering stiffness	7.2	6.6
Aligning torque on rigid body	0.1	−0.1
Roll camber	1.2	0.0
Roll steer	0.5	−0.5
Lateral force deflection steer compliance	0.2	0.2
Aligning torque deflection steer compliance	1.3	0.1
Cornering compliances	10.5	6.3
Total understeer, $D_F - D_R$ = 4.2 deg./g		

CONCLUSIONS

Some changes in vehicle understeer gradient (UG) resulted from the installation of space-saver spare tires on either axle of the 162 vehicles examined. No conclusions can be drawn from the above calculations regarding the braking or highly transient cornering capabilities of a vehicle with a space-saver spare tire installed. However, in the linear range of vehicle operation $a_y \in [\mp{\sim}0.3 - 0.4g]$ at which most vehicles are driven it is reasonable to expect *little change in performance* for many, though not all, vehicles. This was demonstrated by tests reported in a recent popular magazine devoted to vehicle performance and testing, by tests of a T155/60-R18 Maxxis space-saver tire [7].

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Definitions/Abbreviations/Units

Variable	Definition
F_z	tire vertical load (**lb$_f$** or **N**)
A	distance from center of mass to front axle (**in** or **cm**)
B	distance from center of mass to rear axle (**in** or **cm**)
ℓ	wheelbase (**in** or **cm**)
C_i	ith tire cornering stiffness coefficient (**lb$_f$/deg** or **N/rad**)
C_F	cornering stiffness coefficient of front axle (**lb$_f$/deg** or **N/rad**)
C_R	cornering stiffness coefficient of rear axle (**lb$_f$/deg** or **N/rad**)
C_{RF}	cornering stiffness coefficient of right front tire (**lb$_f$/deg** or **N/rad**)
C_{LF}	cornering stiffness coefficient of left front tire (**lb$_f$/deg** or **N/rad**)
C_{RR}	cornering stiffness coefficient of right rear tire (**lb$_f$/deg** or **N/rad**)
C_{LR}	cornering stiffness coefficient of left rear tire (**lb$_f$/deg** or **N/rad**)
W_F	total weight on front axle (**lb$_f$** or **N**)
W_R	total weight on rear axle (**lb$_f$** or **N**)
W	all-up vehicle weight (**lb$_f$** or **N**)
M	all-up vehicle mass (**lb$_m$** or **kg**)
I_{zz}	vehicle yaw moment of inertia (**in-lb$_f$-sec^2** or **kg-m^2**)
UG	vehicle understeer gradient (**deg/g**)
UB	vehicle understeer budget (**deg/g**)
OEM	original equipment
TIRF	Tire Industry Research Facility
HVE	Human-Vehicle-Environment
G	acceleration of gravity (**ft/sec^2** or **m/sec^2**)
U	forward velocity parameter (**ft/sec** or **mp**h or **m/sec** or **km/hr**)
Δ	magnitude of step steer input (**rad**)