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SIMULATION STUDY OF LIGHT-WEIGHTING EFFECTS ON RIDE QUALITY AND MOBILITY

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ABSTRACT

We compared performance of a lightweighted and baseline vehicle and demonstrated how performance is affected by adjusting the spring and shocks using 2-D and 3-D simulations. 2-D lump-parameter model was constructed from physical vehicle parameters by transforming displacements and loads from the springs and dampers into wheel motion and spindle forces. For the 3-D model, a detailed model for each suspension was used including rotational inertia of moving parts. Ride quality was assessed for 16 ride-courses with varying RMS terrain roughness by finding maximum speed at which average absorbed power at the driver seat is lower than 6 W. Shock performance was evaluated by finding maximum speed for the driver not to exceed 2.5-G acceleration when riding over varying-size half-round obstacles. The forces on wheel axes and accelerations were measured for the vehicle dropped from the height of 6, 12, 18, and 24 in. Maximum longitudinal slope climbing capability was estimated on hard and soft soils. The spring rates and shock resistance were varied for the ride, shock, and the drop test to see how these variations affect test results.

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1. INTRODUCTION

Four-wheel drive all-terrain vehicles are constantly being physically modified, often in an effort to reduce gross vehicle weight. Vehicle parameters such as the ratio of the sprung and unsprung mass, torsional stiffness, roll center, center of gravity, and moments of inertia are affected by changing the weight of the vehicle. The changes in weight and vehicle parameters alter the mobility.

Objectives of this work are 1) Assess how changes in weight affect ride quality, 2) Define mobility changes (longitudinal slope climbing) due to light-weighting, 3) Understand effect of changing spring rates and shock resistance on ride quality, shock performance, maximum forces encountered during drop, and longitudinal slope climbing capability.

2. VEHICLE CONFIGURATIONS

The *baseline* vehicle in this work refers to the vehicle before lightweighting modifications at curb weight. The *lightweighted* refers to the vehicle after lightweighting changes at curb weight, which is 19% lower than that of the baseline. The unsprung weight of the lightweighted vehicle was kept the same as baseline, only the sprung weight was lowered during light-weighting.

The *gross* weight, which was 16% higher than the baseline curb weight, was only used in Section 8 to assess the accuracy of VehDyn model by comparison with 3D Chrono simulations.

The springs and shocks were not tuned for the lightweighted vehicle. Instead of optimizing the suspension, single-parameter excursions were made to understand cause and effect relationships when springs and shocks are modified. For clarity, the spring rates changes shown in this study were associated with adjustment in free suspension travel.

3. PERFORMANCE ASSESMENT METHODS

The primary numerical-modeling tool used in this study was the Enhanced Vehicle Dynamics (VehDyn) Module Version 4.3 [1, 3]. VehDyn was developed by the Mobility Systems Division of the Waterways Experiment Station (WES) for general use in support the NATO Reference Mobility Model (NRMM). The VehDyn 4.3 provides a multitude of vehicle simulation capabilities. We used VehDyn to conduct the following tests:

1) Ride limiting speed (Ride Performance)
2) Maximum vertical acceleration during half-round obstacle crossing (Shock Performance)
3) Maximum forces encountered during drop (Drop Test)
4) Longitudinal slope climbing test

Effects of light-weighting were first evaluated by comparing the performance of the baseline and lightweighted vehicle in each of the four categories.

Then, for each of these performance categories, effect of changing spring rates and shock resistance was evaluated to understand cause and effect relationships.

Limitation of the VehDyn Module are:

1) VehDyn can achieve only pseudo three dimensions, called 2.5-D, by simulating both sides of the vehicle in 2-D and combining them together.

2) VehDyn only allows limited alterations to terrain and vehicle characteristics.

3-D simulations to evaluate fidelity of the VehDyn model were performed using the Vehicle module from Chrono Open Source Framework [2] which is currently developed at the University of Parma, Italy and the University of Wisconsin, Madison.

4. RIDE PERFORMANCE

Ride Limiting Speed is a maximum speed achievable while riding over terrain with specified roughness without exceeding 6 watts of average absorbed power at the driver seat.

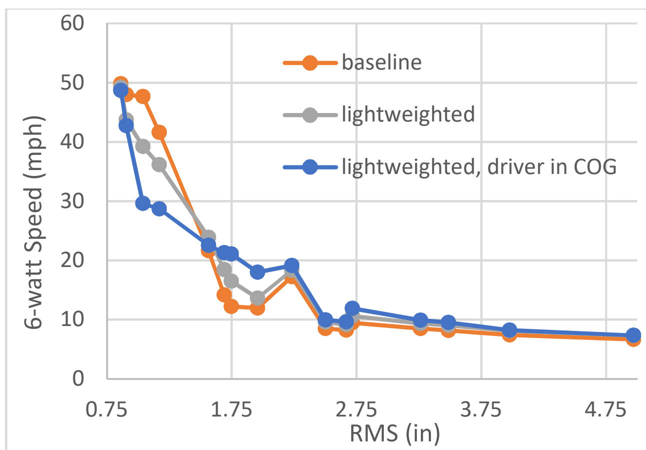

Figure 1: Graphical comparison of ride performance for the baseline (orange color) and lightweighted (grey color) vehicle as listed in Table 1. Blue curve shows lightweighted vehicle with a driver sitting in the center of gravity.

Ride Limiting Speed was estimated using VehDyn by driving the vehicle over 16 ride-courses with increasing RMS terrain roughness. Each vehicle was driven over each ride-course at speeds increased in 5 mph steps. The 6-watt speed was estimated by linear interpolation between two adjacent velocities: the one with absorbed power just below 6 watts and the one with absorbed power just above 6 watts. Estimates of the 6-watt speeds for the 16 ride-courses are shown in Table 1.

Table 1: 6-watt speeds for 16 ride-courses with increasing terrain roughness.

Ride-course	*RMS (in)*	*6-watt Speed (mph)*	
		Baseline	*Lightweighted*
1	*0.86*	*50*	*49*
2	*0.91*	*48*	*44*
3	*1.04*	*48*	*39*
4	*1.17*	*42*	*36*
5	*1.57*	*22*	*24*
6	*1.69*	*14*	*18*
7	*1.75*	*12*	*17*
8	*1.96*	*12*	*14*
9	*2.23*	*17*	*18*
10	*2.50*	*8.5*	*10*
11	*2.67*	*8.3*	*9*
12	*2.72*	*9.5*	*11*
13	*3.26*	*8.5*	*9.3*
14	*3.49*	*8.2*	*9.0*
15	*3.98*	*7.4*	*8.1*
16	*4.97*	*6.7*	*7.3*

First column in Table 1 is a ride-course identifier in the order of terrain roughness. Second column lists the RMS terrain roughness for the track. Third and fourth columns show an estimate of the 6-watt speed for the baseline and the lightweighted vehicle obtained from simulations. 6-watt speeds for the baseline and lightweighted vehicle versus the terrain RMS roughness are plotted in Figure 1.

An instructional study was then performed to understand effects of vehicle weight, geometry, and suspension parameters on the ride performance. The baseline vehicle parameters were changed, one by one in sequence, to those of an unrelated reference vehicle with significantly better ride quality. It was found that, in addition to shocks and springs, the location of the driver's seat and the center of mass location affected the ride quality most significantly. Blue curve in Figure 1 shows that placing the driver in the center of gravity improves the ride performance for ride-courses with RMS greater than 1.5 in, and degrades for ride-courses with RMS lower than 1.5 in.

4.1. Varying Spring Rates

Figure 2 shows how spring rate changes affect ride performance. Ride performance improves with softer springs and degrades with stiffer springs. The improvement in ride performance is marginal for ride-courses with RMS above 3 in due to high RMS ride-courses causing full compression (bottoming out) of the suspension.

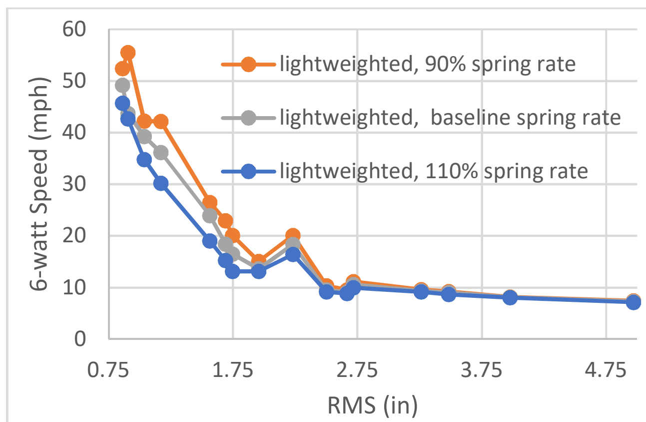

Figure 2: Effects of varying spring rates on ride performance.

For ride-courses with RMS below 2 in, the improvement in ride performance is significant. Low RMS courses do not bottom-out the suspension, that is, the jounce bump stop is reached less frequently, and the soft springs act as a soft cushion between the wheel and vehicle body causing less of the wheel travel being transferred to the chassis and vehicle body.

4.2. Varying Shock Resistance

Figure 3 shows how changes in shock resistance affect ride performance. Ride performance marginally improves with increased shock resistance and degrades with lowered shock resistance for ride-courses with RMS above 1.7 in. This can be attributed to more frequent jounce strike-through events with lower shock resistance at high RMS courses and consequent increase in absorbed energy.

For ride-courses with RMS below 1.7 in, the trend is opposite, with three exceptions where lower shock resistance did not improve but degraded ride performance. Degradation in ride quality with stiffer shocks at low RMS courses can be attributed to increased transfer of wheel movement to body due to higher shock resistance and consequent increase in absorbed energy. Note that accuracy of simulations at high speeds is lower due to finite time step.

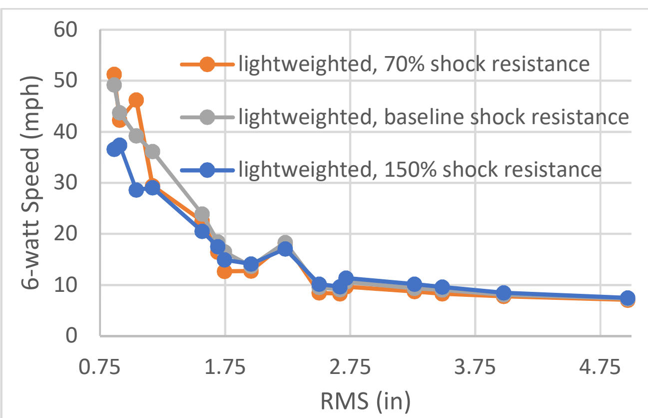

Figure 3: Effects of varying shock resistance on ride performance.

5. SHOCK PERFORMANCE

In a vertical acceleration (shock performance) test, a vehicle is driven over half-round obstacles at maximum speeds without exceeding 2.5-G acceleration at the driver's location. The 2.5-G speed was estimated by linear interpolation between two adjacent velocities: the one with maximum acceleration just under 2.5-G and the one with maximum acceleration just above 2.5-G. Figure 4 compares the performance of the baseline and lightweighted vehicle.

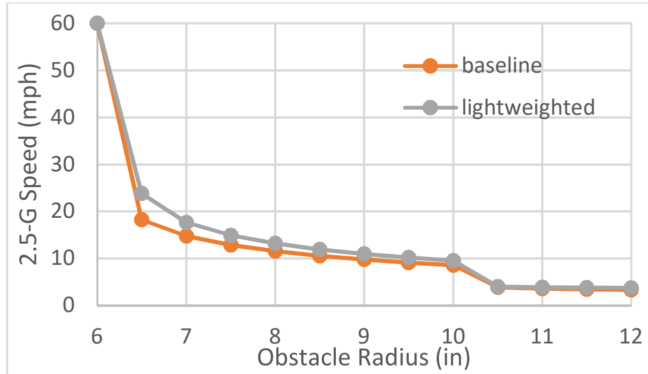

Figure 4: Shock performance of baseline (orange color) and lightweighted (grey color) vehicle.

For half-round obstacles lower than 6 in, the max speed without exceeding 2.5-G acceleration is 60 mph, which was higher than maximum speed for this vehicle. For obstacle radii between 6.5 in and 10 in, the lightweighted vehicle performs better. The improvement of the shock performance from light-weighting is more significant for obstacles with lower radius. For obstacle height of 10.5 in and larger, the maximum speed without exceeding 2.5-G acceleration is close to 4 mph for both baseline and lightweighted versions.

A noticeable decrease in performance between 10.0 in and 10.5 in obstacle is related to an event that generates maximum G. When riding over 10 in and lower obstacles, the max G is reached right after the front wheel collides with the leading edge of the half-round. For 10.5 in and higher obstacles, the max G is experienced shortly after the front wheel passes the obstacle – when it lands on the ground at the time when the front suspension reaches maximum compression state. The jounce bump stop is engaged in both cases.

5.1. Varying Spring Rates

Figure 5 shows how spring rate changes affect shock performance. Shock performance improves with softer springs and degrades with stiffer springs because softer springs with increased free travel will cushion the impact.

Figure 5 shows performance improvements with a reduction in spring rate by 10 percent or 90 percent of the baseline spring rate. For example, when the vehicle travels over an 8 in half round as illustrated in Figure 5, a 2 mph increase in speed can be achieved with a 10 percent reduction in stiffness. Likewise, a 1 to 2 mph reduction in speed is illustrated with a 10 percent increase in stiffness of the spring. Utilizing this information, we can tune the spring rates to offset the change in performance due to changes in sprung and unsprung mass in general.

With lower spring rates, the decrease in performance described at the end of Section 5 will move towards higher obstacles because the vehicle body will elevate less with softer springs.

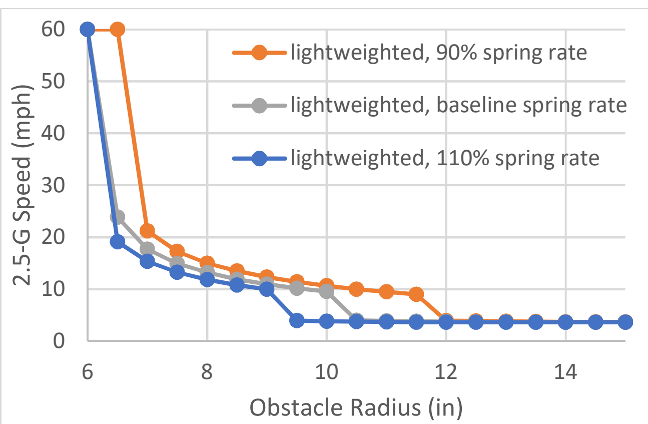

Figure 5: Effects of varying spring rates on shock performance.

As noted in Section 2, changes in the spring rates in this study were associated with adjustment in suspension travel. With lower spring rates the allowed suspension travel was extended, and with higher spring rates it was shortened, so that the same static load is required to reach travel limits for both the baseline and modified suspension.

5.2. Varying Shock Resistance

Figure 6 shows how changes in shock resistance affect shock performance. Shock performance improves with higher shock resistance and degrades with lower shock resistance. Interestingly, the effect from increased shock resistance is similar to the effect from decreased spring rates and vice versa. However, the shocks resistance needs larger percentual change than spring rate to achieve the same effect.

The transition of max G event towards the wheel drop after passing the obstacle, which was mentioned at the end of Section 5, will move towards higher obstacles with higher shock resistance because the shocks will absorb more energy and the vehicle body will elevate less with stiffer shocks. The effect of stiffening the shocks here is similar to lowering the spring rates.

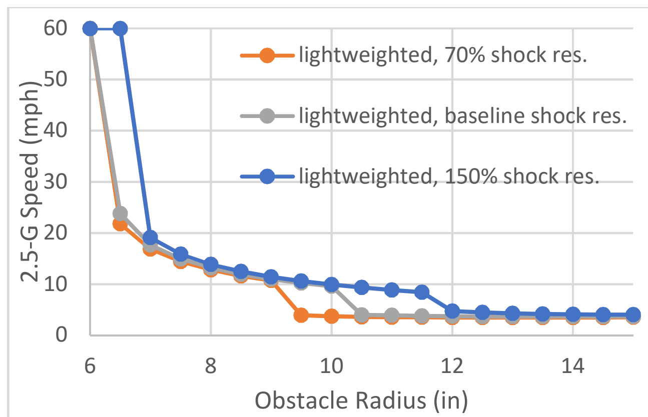

Figure 6: Effects of varying shock resistance on shock performance.

6. DROP TEST

In a drop test, a vehicle is dropped from heights of 6, 12, 18, and 24 in. The vertical force on the wheels and the overall G force on the driver's seat are measured. Figure 7 shows how changing weight affects maximum acceleration during the drop test for the baseline and lightweighted vehicle.

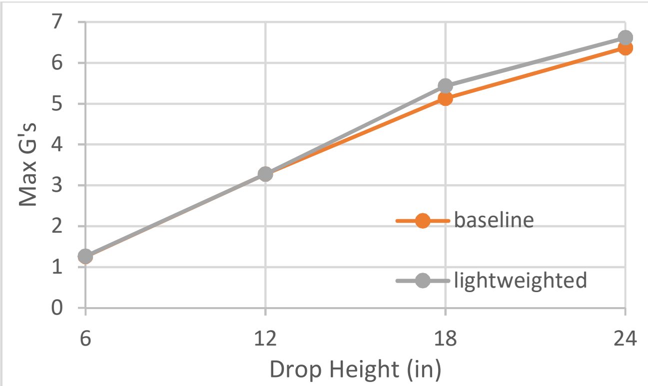

Figure 7: Comparison of maximum acceleration during the drop test for the baseline and lightweighted vehicle.

Higher acceleration is achieved by the lighter vehicle. Since both baseline and lightweighted vehicle have the same suspension, the lower sprung weight will cause lower spring deflection and quick rebound – resulting in higher acceleration. This result is consistent with an assumption that the vehicle will not bottom-out, that is, the vehicle will not reach the lower bound of the suspension travel during the drop. Effects of changing spring rates and varying shock resistance on the maximum G force are presented in Figure 8 and Figure 9.

6.1. Varying Spring Rates

As shown in Figure 8, softer springs result in lower acceleration during the drop, due to softer springs allowing more compression and slower rebound.

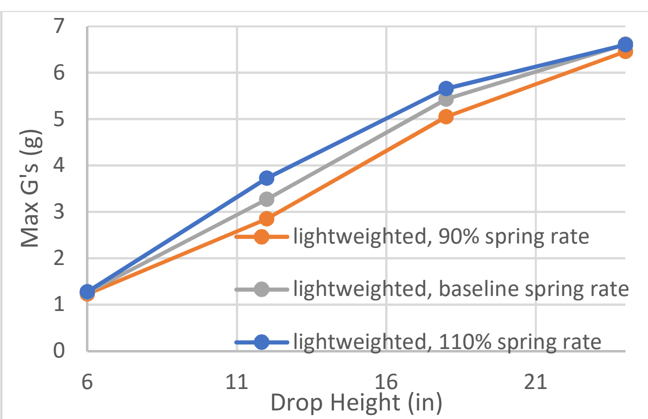

Figure 8: Changes in Max G's for lightweighted vehicle during drop with increased and decreased spring rates.

Stiffer springs, on the other side, allow less compression during the drop and the acceleration is therefore higher.

6.2. Varying Shock Resistance

As shown in Figure 9, increasing shock resistance leads to lower acceleration during drop. This is due to large portion of energy being absorbed by shocks during initial stage of impact. Springs will therefore compress less and produce lower force at the time of maximum compression.

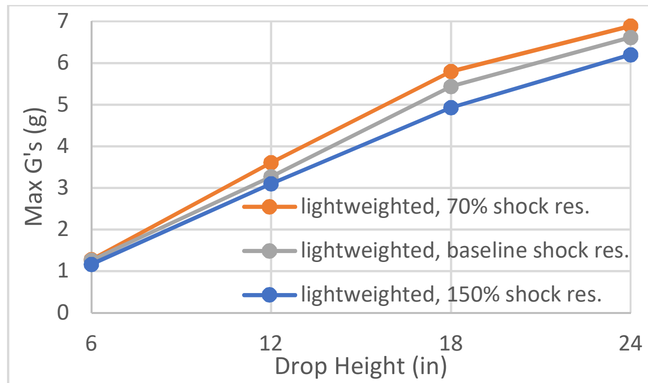

Figure 9: Effects of varying shock resistance on Max G's during drop.

7. LONGITUDINAL SLOPE CLIMB ON HARD AND SOFT SOILS

Longitudinal slope climbing capability was estimated using a vehicle-terrain interface model described in Appendix C of Ref. [3]. The model estimates tractive performance of a wheel based on dimensionless numeric incorporating wheel parameters and soil strength.

Soil strength is characterized in terms of cone index (CI) for loose soil, or rating cone index (RCI) for cohesive soils. RCI is obtained by multiplying the basic CI by remold index (RI). RI represents reduction in mobility due to the cohesive soil displaced by vehicle traction. RCI values examined here were 60, 100, 150, 200, 250, 300, and 350 PSI. RCI value of 300 PSI represents a hard surface where wheel load results in nearly negligible deformation.

Wheel parameters are the nominal diameter, tire section width and height, tire deflection, and weight beneath tire. Variants of numeric were developed at WES for clay, sand, powered, and towed wheels [3]. These can be applied to predict drawbar pull, motion resistance, drive torque, slip, and sinkage. The theoretical tractive force available from the vehicle propulsion system is adjusted using soil properties, wheel parameters, and the appropriate numeric to obtain soil-adjusted tractive force, which is used to determine longitudinal slope climbing capability. The *db-based* maximum % grade is obtained from maximum available soil-adjusted tractive force as tan(fmax/weight) *100%. The *dynamic* maximum % grade is obtained by a sequence of attempts to climb 0%, 100%, 50%, and then 25% or 75%, etc. slopes. The climb starts with the speed of 1 mph. The sinkage, pull, and speed are calculated dynamically. If the vehicle sustains non-zero speed at the given slope, the slope is increased in the next attempt, otherwise decreased, until the max grade is found with desired accuracy.

Table 2 compares the numerical estimates of longitudinal slope climbing capability for the baseline and lightweighted vehicle on sand-silt mixtures with RCI = 300 PSI.

Method	Baseline Max grade	Lightweighted Max grade
DB-based	80.9%	81.2%
Dynamic	74.6%	75.2%

Table 2: Maximum slope: baseline vs. lightweighted version on sand-silt mixtures with RCI = 300 PSI.

For a given vehicle, the estimated maximum longitudinally climbable grade will depend on the strength of soil given by RCI. Effects of soil strength are illustrated in Figure 10 and Figure 11. The maximum grade on sandy soils is much higher than on clays due to high plasticity and cohesive properties of inorganic clays. In general, the gradeability will deteriorate on softer soil. On sandy soils, however, lowering the strength from 350 to 100 PSI will improve the gradeability due to better grip, and the deterioration is observed when the strength is lowered further from 100 to 50 PSI.

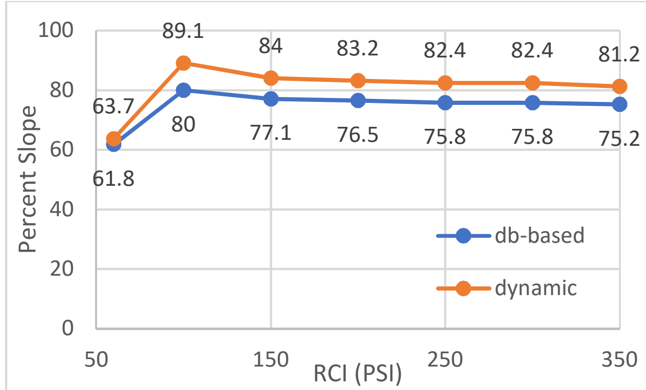

Figure 10. Longitudial slope climbing on silty sand.

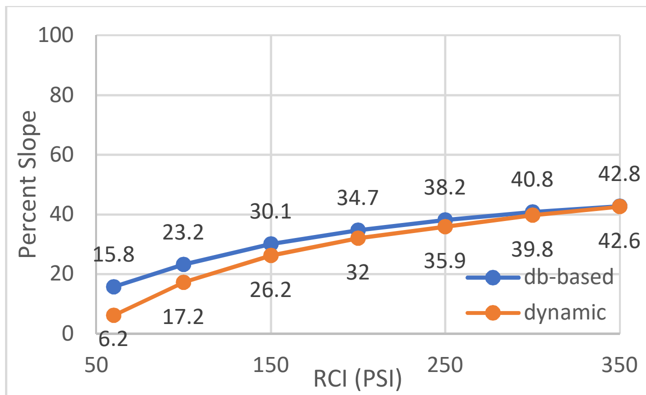

Figure 11. Longitudial slope climbing on high-plasticity inorganic clays.

Reducing unsprung weight and changes in spring rates or shock resistance do not significantly affect the gradeability. As expected with sufficiently powerful engine and a low first gear ratio, the slippage between the wheel and soil are the limiting factor.

8. 3D SIMULATIONS

Detailed 3D vehicle simulations produce more accurate results than 2D lump-parameter models. Improved accuracy comes at the cost of model complexity, increased number of parameters, and longer computational time. Accuracy of the

VehDyn performance predictions in this work was assessed by comparison with 3D simulations using Vehicle module from Chrono software package [2].

Shock performance predictions from Chrono are compared with VehDyn in Figure 12 while the ride performance predictions are compared in Figure 13. As described in Sections 3 and 4, the speed applied in the simulations was increased in 5 mph steps and the limiting speed was obtained by linear interpolation between above-limit and below-limit speed according to acceleration and absorbed power.

Shock performance (Figure 12), which is characterized by the maximum obstacle-crossing speed without exceeding 2.5-G acceleration at the driver seat, was found to strongly depend on the tire model. 3D simulations using Chrono Vehicle module deployed four semi-physical tire models: TMEasy tire model [4] without belt dynamics, and Fiala and Pacejka89 tires models [5]. VehDyn tire model predicted most conservative 2.5-G speed estimates, while the TMEasy tire permitted the highest speed.

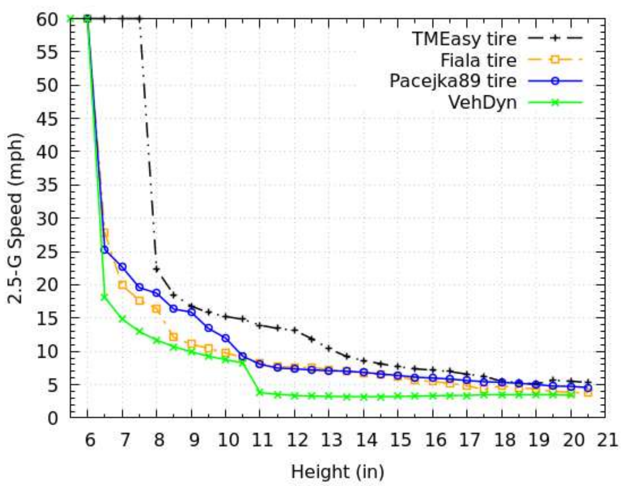

Figure 12. Baseline shock perfomance at gross weight: 3D simulations with three different tire models versus VehDyn.

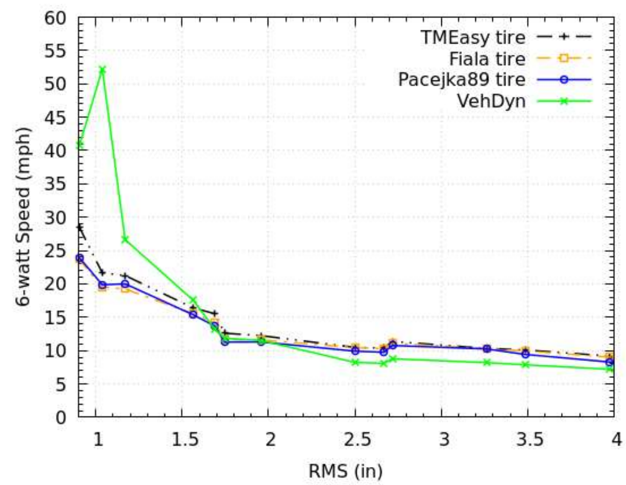

Figure 13. Baseline ride perfomance at gross weight: 3D simulations with three different tire models versus VehDyn.

Ride performance predicted by the 3D model is compared with VehDyn prediction in Figure 13. 3D results are close to VehDyn except at high speeds that are permissible at terrains with RMS below 1.5 in. The discrepancy at high speeds can be attributed to significant effect of rotational inertia from moving components of suspensions.

9. CONCLUSIONS

Reducing weight affects the *ride quality*. The baseline vehicle performs significantly better than lightweighted on ride-courses with low terrain roughness. On ride-courses with high roughness, the lightweighted vehicle performs marginally better than baseline.

Reducing weight improves the *shock performance*. A consistent improvement is seen for the lightweighted vehicle.

For the 6-inch and 12-inch *air drop*, maximum encountered accelerations for the baseline and lightweighted vehicles do not differ significantly. For 18-inch and 24-inch drop heights, lower-weight versions encounter higher max accelerations, with the Max G increase of approximately 5%.

Gradeability was only marginally improved by light-weighting.

Lower spring rates along with increased suspension travel improve the ride and shock performance and decrease the maximum force encountered during the drop for the lightweighted vehicle. Higher shock resistance for the lightweighted vehicle improves the shock performance, lowers the maximum force encountered during the drop and improves the ride performance for ride-courses with high roughness.

These finding resulted from numerical prediction for a vehicle under investigation, however, similar trends are expected for light-weighting in general.

10. ACKNOWLEGMENT

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