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Sensitivity Analysis of Various Vehicle Dynamic Simulation Software Packages Using Design of Experiments (DOE)

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Abstract

A previous paper on this topic presented the use of design of experiments (DOE) to evaluate the sensitivity of vehicle dynamics simulation of the postimpact motion of a vehicle that included high initial rotational rates. That investigation involved only one software package and thus was confined to one simulation model for the purposes of developing and refining the analysis method rather than including a variety of simulation models for broader application. This paper expands the application of the method to investigate the comparative behavior and sensitivity of several other vehicle dynamic simulation models commonly used in the field of crash reconstruction. The software packages included in the studies presented in this paper are HVE (SIMON and EDSMAC4), PC-Crash and VCRware. This paper will present the results of the study, conducted using DOE, involving these models. The eleven factors selected for the study presented here were chosen based largely on the results of the prior study. The experimental design was expanded from 16 trials to 32 trials to provide additional insight into the interactions between the factors. Three response variables were used: the *x*-coordinate, *y*-coordinate and total rotational displacement of the vehicle at rest.

The results of the analysis show the sensitivity of all four programs to the eleven factors as well as the interactions between the factors. The results show that, consistent with prior results, and the expectation of the authors, the factor that all four programs showed as the most sensitive is the tire-roadway drag. Additionally, consistent with a reconstructionist's intuition, is that the programs are sensitive to the initial (postimpact) velocities. However, the level of the sensitivities of the four programs to a given change in the same factor are different in many cases.

As compelling as the results are that show the largest sensitivities, the results show factors that some, or all, of the programs show little sensitivity. For example, for response using the *y*-coordinate and rotational displacement of the vehicle at rest, all four of the programs were relatively insensitive to changes in the lateral and longitudinal stiffnesses of the tires over the range selected.

Introduction

The motive behind the paper that preceded this one [1] focused on establishing the use of design of experiments (DOE) as a method for the exploration of the sensitivity of a vehicle dynamics simulation model. The number of input values associated with a system as complex as a vehicle dynamics simulation program presents a computational (and temporal) challenge to assess the sensitivity of a model to variations in numerous parameters. The use of DOE for this task proves quite effective [1]. Additionally, DOE implicitly provides a means to evaluate the interactions of the parameters which is not necessarily available with other methods that assess sensitivity. Thus, the method provides a means to understand the trade-offs associated with the change in one parameter of a simulation producing a desired effect in one aspect of the results (e.g. the *x*-coordinate of the rest position of the vehicle) and an undesired effect in another aspect of the results (e.g. the final angular orientation of the vehicle). These types of trade-offs are encountered routinely by reconstructionists in project work in reconstructing vehicle motion while trying to match the physical evidence. Changes introduced by the reconstructionist in certain parameters produce an improved match in one aspect of the physical evidence but often leads to a worsening match in another aspect of the physical evidence.

The first paper was initially intended to include the evaluation of various vehicle dynamics simulation models used in the field of crash reconstruction, but the approach required development and refinement before the method was deemed reliable. Thus, the first paper addressed various development issues and then evaluated only one vehicle dynamics simulation model. While focusing on the one model, results related to analysis from experimental designs with four different sets of factors and two different collision geometries were analyzed.

The results of the analysis showed that of the common factors that were used in all simulation experiments, several were significant in all the trials. The common significant factors are tire-roadway frictional drag, *f*, the CG height, h_{CG}, and vehicle mass, *m*. Other factors that also were significant were aerodynamic drag, initial velocities, longitudinal position of the CG and the yaw inertia. Each of these factors were not included in every analysis but were significant when included. The significance of the initial conditions was not surprising to the authors. This shows the importance of the results of the modeling of the impact (which produces the initial velocities of the postimpact motion, i.e. the initial conditions for the postimpact motion) in the accuracy of the simulation of the postimpact motion. The significance of aerodynamic drag was a surprising result to the authors.

That initial analysis and the accompanying results helped guide the analysis presented in this paper. The analysis here differs from the previous analysis in two principal ways. First, four different simulation models are included in the analysis rather than just one. This allows for the comparison of the behavior of these models to changes in the same factors (input parameters). The software programs included in the analyses are PC-Crash [2], SIMON [3], EDSMAC4 [4] and VCRware [5]. These vehicle dynamics simulation programs, particularly the first three, appear to be the most commonly used simulation programs in the field of crash reconstruction in North America.

Second, the number of trials used in the DOE was doubled from 16 to 32. These additional runs allow for better assessment of the nature of the interactions between the various factors selected in the DOE.

The intent of including various simulation models in this study is not to evaluate the "rightness", "wrongness" or address the validation of the models. The authors expect that the various models will produce different results. This difference in model results is referred to as "model" uncertainty, that different models will produce different results. This supports the expectation that the sensitivity of the different models to changes in the same parameters will also differ. This paper examines that topic.

Readers of this paper might be interested primarily in one of the simulation models with perhaps not as much interest in the other three models. Taken individually, the results pertaining to each of the models provide the reader with insights into the sensitivity of that model to the parameters (factors) included in the study. These results will hopefully motivate the reader to further examine the use of their preferred model as it pertains to his/her reconstruction work. The authors suggest that users of a given simulation program fully understand their program of choice. The sensitivities of the models presented here contributes to that understanding. Last, this paper provides another example of the use of DOE in the analysis of uncertainty and sensitivity in the field of crash reconstruction.

The approach to the application of DOE in this paper follows the development of the method presented previously [1]. That is, the method implements DOE by prescribing the initial velocity and location of the vehicle (while varying parameters) and uses the rest position and orientation of the vehicle as the response variable. In this way, the DOE analysis can be used to assess the sensitivity of one of the programs to the changes in the parameters, including the components of the initial velocity: the larger the changes to the rest position and orientation resulting from changes in the parameters provides the sensitivity of the program. The authors recognize that the use of the simulation programs in this manner is different than would be typical in a reconstruction application. In that manner, the parameters and initial velocity components are changed to achieve a desired rest position. This "reconstruction" approach would require development to validate this application of DOE methods. This alternative approach is deferred to future research.

Analysis Method: Design of Experiments (DOE)

The formulation of the concepts of the design of experiments (DOE) originate in the beginning of the 20th century. Numerous treatments of the topic exist containing the details of the method [11, 12]. Generally, the DOE method is used with experimental measurements of a physical system or physical process. DOE is an analytical method in which changes in the response of the system or process due to changes in the factor values is determined and analyzed. The details of the method are too numerous to present here. Readers interested in these details will find many books dealing specifically with this topic as well as many statistics books also including this topic.

The method can be applied to computer "experiments", i.e. computer simulations. The application of the use of DOE applied to computer simulation has been a more recent development. Early work was done in the late 1970's and early 1980's [13, 14] with the advent of widespread availability of digital computers and development of simulation models. The topic now is given its own treatment in various books [11, 15] and has been included in books dealing with forensic engineering applications [16].

The application of DOE used here belongs to the category of 2^k Fractional Factorial Design. In this DOE construct, each of the k factors selected in the analysis has two levels, or values, generally designated as high/low (or +/-) relative to a nominal value. If the number of factors, k, becomes large, then 2^k becomes large, requiring numerous trials. An approach can be used whereby the number of trials can be reduced by p half fractions with little loss in effectiveness by considering that, with many factors, the effects of higher-order interactions are likely to be negligible. The number of runs is reduced from 2^k to 2^{k-p}. With this approach, the specific DOE method used is referred to as a Fractional Factorial Design.

Readers interested in the details of DOE methods will find copious resources available. Several references suitable for an initial study are here [11, 12, 15, and 16].

The experimental design requires the identification of a response of the process. The system response used in the analysis presented herein is selected based on the reconstruction task. Generally, a reconstructionist will endeavor to match the simulation response to the available physical evidence. The physical evidence associated with the postimpact motion of a vehicle typically used as the acceptance criteria of the simulation of vehicle postimpact motion is the rest position and orientation. Thus, the two coordinates of the CG of the vehicle at rest (x, y) and the rotational displacement (θ) are used here as the response of the vehicle postimpact motion.

In this application, the number of factors, k, is eleven. Each of the factors is assigned high and low values. In keeping with the Fractional Factorial design, each of the four simulation programs is run 32 times, with 2^{k-p} being 32; thus $(k-p) = 5$ in this application. Appendix B lists the DOE structure used in the analysis with 11 factors, providing the level of each of the eleven parameters for the 32 trials. The specific numerical values of each of the factors is provided in the next section.

The design of the DOE permitted the development of a linear model of the form:

$$y = \beta_0 + \sum_i \beta_i \cdot X_i + \sum_i \sum_{j>i} \beta_{ij} \cdot X_i \cdot X_j + \epsilon$$

where,

- β_0 is the y-intercept
- β_i is the coefficient associated with the Main Effect of the i^{th} factor
- β_{ij} is the coefficient associated with the 2-Factor Interactions
- ϵ is the Error Term

The β terms are the average effects associated with the respective factors, i.e. change in the response for a unit change in the individual factor, given the remain factors would remain constant. Note that this design of the DOE allows for discerning 2-factor interactions, but 3-factor interactions and higher level interactions cannot be discerned.

The Factors

The factors that were selected for the DOE analysis presented here are listed in Table 1. These factors were chosen based primarily on the results of prior analysis [1] and on the experience of the authors in using the various programs. Influencing the selection was the recognition that the parameters with recognizable variation are better candidates for inclusion as factors in the DOE. Examples of input parameters with negligible variation, and thus not a good candidate for this type of uncertainty study, are the track width, steering ratio, ground clearance or roof height. The reason for this is that these dimensions for virtually all vehicles are available in a variety of databases for vehicle specifications with high accuracy and is invariant to other parameters (such as vehicle weight, etc.). Therefore, it rarely, if ever, needs to be measured and is not subject to measurement uncertainty and can be considered to have no variation. (Exceptions to this would be a modified vehicle or a vehicle that has a chassis that is damaged in a collision.)

TABLE 1 Factor ranges used in the DOE analysis

#	FACTOR	LOW	NOMINAL	HIGH
1	Wheel Lateral Stiffness (C_α) [lb/rad]	12,350	13,000	13,650
2	Wheel Longitudinal Stiffness (C_α) [lb/(unit slip)]	9500	10,000	10,500
3	Weight [lb]	3027	3186	3345
4	Yaw Inertia [ft-lb-s^2]	1900	2000	2100
5	CG Height [ft]	1.71	1.76	1.81
6	Tire-Road Frictional Drag [-]	0.65	0.70	0.75
7	Front Wheel Steer Angle @ wheel [deg]	-5.0	0.0	5.0
8	Aerodynamic Drag [ft^2]	OFF	OFF	ON
9	Initial Lateral Velocity [ft/s]	17.71	18.17	18.62
10	Initial Longitudinal Velocity [ft/s]	-57.56	-59.04	-60.51
11	Initial Angular Velocity [°/s]	-425.71	-436.43	-447.48

In contrast, the CG height of the vehicle is very difficult to measure, requiring special equipment and is not invariant with other vehicle parameters (e.g. loaded weight, etc.). Therefore, for crash reconstruction and vehicle dynamics simulation, this parameter is always estimated by the analyst (or estimated and assigned by the simulation program) in some manner. Uncertainty such as that associated with CG height makes this parameter, and similar input parameters, natural candidates for sensitivity analysis. For this analysis the CG height were referenced from using a published estimation method [22].

Table 1 lists the eleven parameters and the associated units as well as the NOMINAL, LOW and HIGH values used in the DOE analysis. The magnitudes of the three components (v_x, v_y, and θ) of the initial velocity were varied by the same percentage such that the initial kinetic energy of the vehicle increased or decreased by approximately 5%. The nominal weight of the vehicle was taken from [19]. The CG height of the vehicle was estimated using the methodology presented previously [22]. The other inertial parameters are appropriate estimates and are maintained across the simulation programs for proper comparison.

In all cases treated here a wind speed of zero is used. The aerodynamic drag is a resultant force calculated using frontal and lateral components. A frontal drag coefficient for all simulations had a value of $C_{dF} = 0.4$ with a frontal area of $A_F = 25$ ft^2 (2.3 m2). The corresponding lateral or side values are $C_{dL} = 0.8$ and $A_L = 60$ ft^2 (5.6 m^2). For no aerodynamic drag $C_{dF} = C_{dL} = 0$. In some cases, an aerodynamic moment (usually small) is developed since the side force is not aligned with the vehicle center of gravity. When included, a moment arm of 0.76 ft to the rear of the CG was used.

Given the differences in magnitude of the range of the different factors, coded units were used in the analysis of the DOE results. This means that, prior to the analysis, factor levels were coded between -1 and +1 for the respective low and high limits. Coding the data this way provides for a more accurate result when performing the Analysis of Variance (ANOVA) [11].

Appendix B lists the DOE structure used in the analysis with 11 factors, each at two levels, and 32 trials (or runs). Note that the "-" and "+" values represent the low and high values as presented in Table 1.

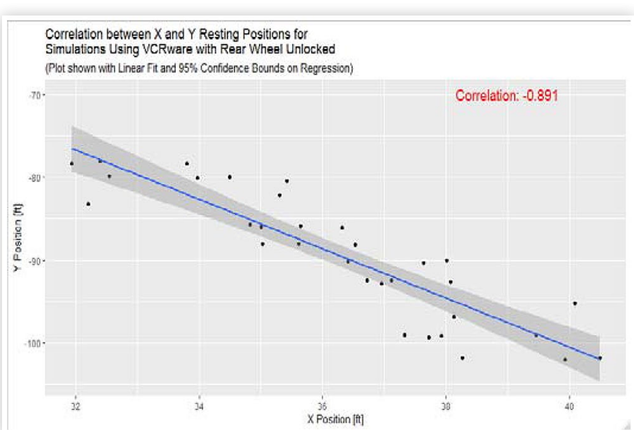
Response - Dependent Variable

The response variables for analysis were the *x*-coordinate, *y*-coordinate and total rotational displacement of the vehicle at rest. Separate models were built for each variable for each software package - 15 separate models in total (including VCRware Locked and Unlocked).

Combining the response variables using combinations of these variables, e.g. total distance traveled, was not possible given the correlation of the response variable with each other. Producing linear combinations of these correlated variables will result in an increase in the Expected Variance of the function results.

An example of the correlation of the response variables is shown in Figure 1.

FIGURE 1 Example of correlated response variables X and Y positions for VCRware with Unlocked Rear Wheel.



The Simulation Models

The software programs included in the analyses are PC-Crash [2], SIMON [3], EDSMAC4 [4] and VCRware [5]. The four sections that follow provide background for each of these simulation models. These sections are not meant to include all the technical details of the model. Rather, they provide an overview for each of the simulation programs and context related to the analysis included in this paper. This context helps in the understanding of the models by the reader. Coupled with the data provided for each of the programs in the appendices for the nominal run, sufficient information and data are provided for the DOE to be duplicated.

HVE (v. 14.00) - EDSMAC4

EDSMAC4 is one of the reconstruction models available within the software HVE. It is an extended version of the collision and vehicle dynamic models of its original version, EDSMAC, which was introduced in 1985 [9]. There are several papers that describe the model and validate its use [24]. EDSMAC4 is an extension of the original EDSMAC involving three major portions of the original code: control routine logic, collision algorithm, and vehicle dynamics model. The latter of these three capabilities produces the results of EDSMAC4 involved in the analysis presented in this paper. EDSMAC4 uses a fixed timestep, fourth-order, Runge-Kutta numerical integration method that calls another function which in turn calls the routines that calculate the forces and moments acting on the vehicle. The position and velocity of the vehicle center of mass are then updated for the next time step. This process is repeated until a termination condition occurs. Examples of termination conditions are, but not limited to, either that the vehicle stopped (minimum speed) or the maximum simulation time defined by the user was reached.

The vehicle dynamics model is a 3-degree-of-freedom (per vehicle) system simulating *x*-*y* translation and yaw rotation (Ψ) with motion in the *z* direction, roll and pitch orientations calculated on a quasi-static basis [9]. The model calculates tire slip angles, the vertical tire load, the tire forces in the plane of the road and the moments of these forces about the CG. Slip angles are calculated from the wheel's current forward and lateral velocities. EDSMAC4 does not include suspension characteristics, therefore the roll couple distribution is used to distribute lateral forces between the front and rear axles. The program uses the friction circle and the Fiala tire model [23] to calculate tire longitudinal and lateral forces.

The user can control various properties of the vehicle, the environment, and the event with the values entered via an editor. For the analysis presented here, the vehicle was selected from the existing HVE vehicle library and as such, its geometry was unaltered and wheel/tire location and sizes kept as default. Where appropriate, the factors listed in Table 1 were unit converted to match units accepted in HVE, and for the specific case of initial velocities, the resultant and direction were calculated and implemented. The values for factors 1 through 5 were entered in the Vehicle Editor. In the Environment Editor, the environment chosen was the "proving grounds", a general pre-defined flat roadway environment. The tire-road frictional drag, factor 6, was edited in the Environment Editor as well by assigning a terrain friction multiplier [25]. Factors 7 and 9 through 11 were entered in the Event Editor. Also entered in the Event Editor were changes to the powertrain and rolling drag under the Driver Controls tables. The powertrain and rolling drag were calculated based on changes in weight for each trial. The powertrain and rolling drag were 10% and 0.7% of static normal force, respectively. The integration time step was 0.001 second. The final *x*, *y* and total Yaw displacement (Ψ) for each run was recorded.

The EDSMAC4 simulation model does not include aerodynamic forces. Thus, the sensitivity of the simulation program to this parameter could not be evaluated. The detailed inputs of the nominal run for HVE EDSMAC4 are presented in Appendix C.

HVE (v 14.00) - SIMON

SIMON is another physics model available within the HVE software. It was developed as an adaptation of previous vehicle-dynamics simulators available within the HVE software and was specifically designed for the HVE interface. The simulation program utilizes 3D vehicle models each with the capability to support up to 21 degrees of freedom (6 DOF for the sprung mass, and up to 5 DOF for each of the axles). The user can assign numerous properties for the vehicle including the initial position, the six initial velocities and driver controls (such as steering, braking, throttle, and gear position). Three initial velocities were used for this case: longitudinal, lateral and rotational yaw.

As with the EDSMAC4 analysis, the vehicle was selected from the existing HVE vehicle database for the purposes of this paper. Its overall geometry was unaltered, and most predefined parameters were kept as default values. Properties for factors 1 and 2 were altered using the "longitudinal stiffness" and "cornering stiffness" values, both located within the Tire Properties dialog. Factors 3 and 4 were edited through the Inertial Data dialog box. The CG height location was varied and testing through simulation until the steady-state CG position matched the intended target. Similarly, frictional drag was determined by varying road surface friction factors until steady state simulations showed overall drag factors matching target values. All the remaining factors were edited directly in the Event Editor.

Simulation event settings included utilizing the semi-empirical tire model (Version 2), and fixed Runge-Kutta integration timestep at 0.001 second. The detailed inputs of the nominal run for HVE SIMON are presented in Appendix D.

PC-CRASH (v. 11.0)

The vehicle dynamics simulation program in PC-Crash is widely accepted and validated for the simulation of motor vehicle accidents, covering many different accident situations [10, 26].

The input parameters of the program include geometric properties, (e.g. wheelbase, track widths, etc.), vehicle inertial properties (e.g. vehicle mass, yaw inertia, CG height, etc.), parameters associated with the TM-Easy tire force model (*Fmax, Fslip*, etc.), environmental parameters (e.g. tire roadway friction, f) and initial conditions (v_x, v_y, and ω).

Some of the initial parameters used for the purpose of this paper needed to be adjusted to fit in PC-Crash's specific program. For example, the lateral and longitudinal velocity components needed to be converted to a resultant velocity with a departure angle (similar to EDSMAC4). The wheel lateral and longitudinal stiffness values also needed to be adjusted to fit within the TM-Easy tire model. This was done by converting the lbs/unit slip values designated for wheel stiffness to kN and using those values for F0_p in the TM-Easy tire model. The remaining values in the TM-Easy model were set using the PC Crash user's manual, matching the stiffness slopes generated within PC-Crash to the desired values listed in Table 1.

PC-Crash's coordinate system is also defined differently from the other programs. PC-Crash views x as positive to the right, y as positive upward, and z positive out of the screen. Adjustments for consistency were made for proper comparison between the models.

The output of the model is the motion of the vehicle. This motion is visualized through the position of the CG with respect to time in the x-y plane (compared to the original position at the origin of (0,0)), as well as the rotation of the vehicle about its z axis. Each simulation was run with an integration time step of 0.005 seconds. The detailed inputs of the nominal run for PC-Crash are presented in Appendix E.

VCRware (v. 3.3)

The work in this study uses the vehicle dynamics simulation model that is part of the VCRware® computer software suite [5]. The details of the model and the validation are presented elsewhere [6]. This simulation model is for a two-axle, four-wheeled vehicle pulling a semitrailer. The tire forces are modeled using a nonlinear tire force model. The details of the tire force model are presented in detail elsewhere [7, 8]. The application here did not involve a semitrailer thus the model for the vehicle motion is just using the two-axle vehicle resulting in a three degree-of-freedom system. The differential equations of motion are put in first order form and are integrated using a Runge-Kutta-Gill numerical integration scheme. The result is the motion of the vehicle (the x-y position of the center of mass and the angular rotation) for a given set of initial conditions (the initial position and the initial speeds) and set of vehicle parameters. The vehicle model does not include a suspension but does include dynamic weight shift requiring that the height of the vehicle center of gravity (CG) be defined.

The input parameters of the program include geometric properties, (e.g. wheelbase, track widths, etc.), vehicle inertial properties (e.g. vehicle mass, yaw inertia, CG height, etc.), parameters associated with the tire force model (C_α, C_s, etc.), environmental parameters (e.g. tire roadway friction, f) and initial speeds (v_x, v_y, and ω).

The output of the model is the motion of the vehicle (the successive positions of the vehicle CG) and the angular position (heading) as a function of time. The "sampling rate" of the motion is the time-step of the Runge-Kutta-Gill integration procedure. The analysis conducted here did not include the time-step as a factor in the DOE analysis and it was fixed throughout the analysis runs at 0.005 seconds. The detailed input values of the nominal run for VCRware is presented in Appendix F.

Simulated Crash

This analysis follows work done in two papers. In [17], a sensitivity analysis of vehicle dynamics simulation to impact induced steering is presented for vehicles with high initial rotational speed. In [18], different vehicle dynamics simulation programs were analyzed and compared using experimental data that was previously presented [19]. The vehicle used in the driving tests presented in [19] was a 1991 Honda Accord EX-R four-door sedan equipped with an automatic transmission. This same vehicle was studied in [20] including generalizing the tire model amongst the various simulation packages included in this paper. This generalization of the tire models (and the simulation parameters as presented in [20]) is used here again for consistency in the comparison of the results of the DOE analysis.

Figure 2 shows the impact orientation of the two vehicles that resulted in the post impact dynamics for the Honda studied here using DOE. This impact is modeled using planar impact mechanics (PIM) [21] to generate realistic initial conditions for the simulation. The crash geometry and conditions are meant to mimic those of a perpendicular intersection with one vehicle failing to stop for the traffic control system. Prior to impact, neither vehicle has an initial angular velocity and neither vehicle is braking. The impact analysis produced the initial conditions for the Honda Accord shown in Table 2. These values are used as the nominal condition in the DOE analysis. The output sheet of the PIM analysis is included in Appendix A. The second vehicle involved in the collision is a 2005 Ford Crown Victoria.

In addition to the factors in the analysis as listed and described above, it is important to understand other vehicle conditions that affect the response of the vehicle. However, in this situation, the vehicle conditions are kept constant through all the runs. The main example of this is the condition of the left rear wheel. In previous analysis [1], all the wheels were free to rotate with longitudinal slip added that represented driveline drag, rolling resistance and other secondary slip. In the analysis presented here, this wheel is locked ostensibly due to impact damage. This influence of this particular condition is evaluated, and the results are presented below.

FIGURE 2 Impact geometry for the crash used with PIM to generate the initial conditions for the DOE analysis. The location of the impact center is indicated by the dot. Both vehicles initial velocities were 50 mph. Large arrows indicate direction of preimpact velocity of each vehicle.

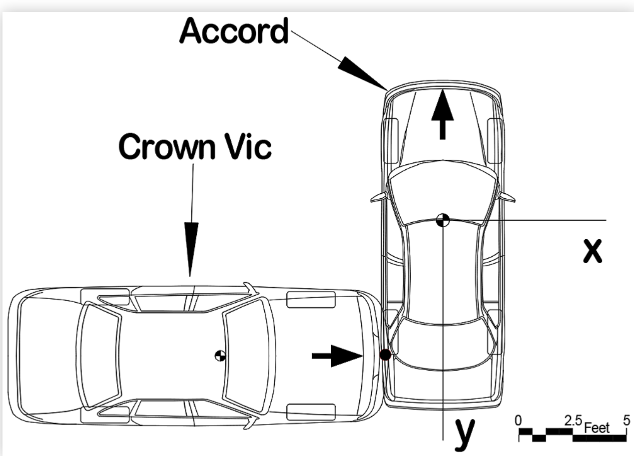


TABLE 2 Results of the impact analysis yielding the nominal initial velocity conditions for the Honda Accord used in the DOE study.

Postimpact velocity in *x*-direction (Accord)	18.17 ft/s (5.54 m/s)
Postimpact velocity in the *y*-direction (Accord)	59.04 ft/s (18.00 m/s)
Postimpact angular velocity (Accord)	436.43 deg/sec

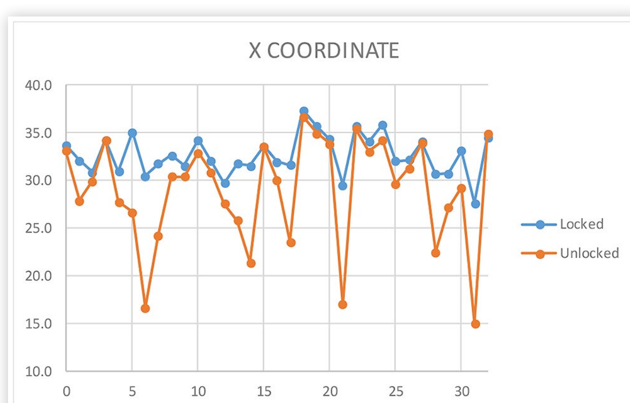
Before presenting the results of the four programs, analysis of the sensitivity of the VCRware model for the locked and unlocked wheel conditions is presented. This provides an introduction to the DOE analysis and insight into the effects of the longitudinal slip condition of the left rear wheel.

Results

This section is comprised of two phases. The first phase presents results that deal with differences seen using results generated with only one of the programs, VCRware. This comparison was made prior to the analysis involving the four programs to evaluate the general effect of the wheel conditions. The analysis in the previous paper had all four wheels of the vehicle free to roll with prescribed slip to account for driveline drag. The analysis comparing the sensitivity of these two different wheel conditions showed that the results are different. Based on these differences, the authors decided that the sensitivity comparison in the second phase would be conducted with the left rear wheel of the vehicle locked. The results of these two phases are presented next.

Phase 1: VCRware was used in the original paper [1]. In [1], the analysis was conducted with all four wheels unlocked, while the simulations performed in this study were made with only the left rear wheel locked. To assess the effect of the wheel conditions, a comparison was made using VCRware, where simulations were performed using the DOE strategy described earlier, with one set of experiments performed with all wheels unlocked (but with appropriate drag) and again with the left rear wheel locked (with the other three wheels with the same appropriate drag). The strategy included 32 runs for each of the two wheel conditions. The 32 runs adhered to the values of the factors as dictated by the structure given in Appendix B to accommodate the DOE analysis. A comparison of the *x*-coordinate response via simulation results is shown in Figure 3.

FIGURE 3 Comparison of resting x-position for simulations with unlocked and locked rear, left wheel as obtained using VCRware. (Trial 0 is the result for the nominal values.)



This locked/unlocked comparison is included here as the authors might question whether the LR wheel of the Accord might be locked due to damage from impact. This example is included here to show how the handling of this condition produces different results, as is expected. In the case of an actual reconstruction of similar postimpact motion of a vehicle, this physical condition of the wheels should be evaluated during the inspection of the vehicle. This can be done by physically rotating the wheel if a visual assessment regarding rotation is inconclusive. VCRware is used here to study such a situation.

Figure 3 shows a resting x-position for the 32 simulations performed with the left rear wheel locked, relative to those with the left rear wheel unlocked. When comparing consecutive trial runs, there were 25 trials that were in agreement with regards to the direction of change that the trial settings had on the resting x-position - there were 6 runs that were in disagreement. For example, when comparing DOE trials 1 and 2 in Figure 3 with the wheel unlocked to the wheel locked, the change in the x-position was increasing for unlocked, while for the same two simulation trials with the wheel locked, the change in the x-position was decreasing.

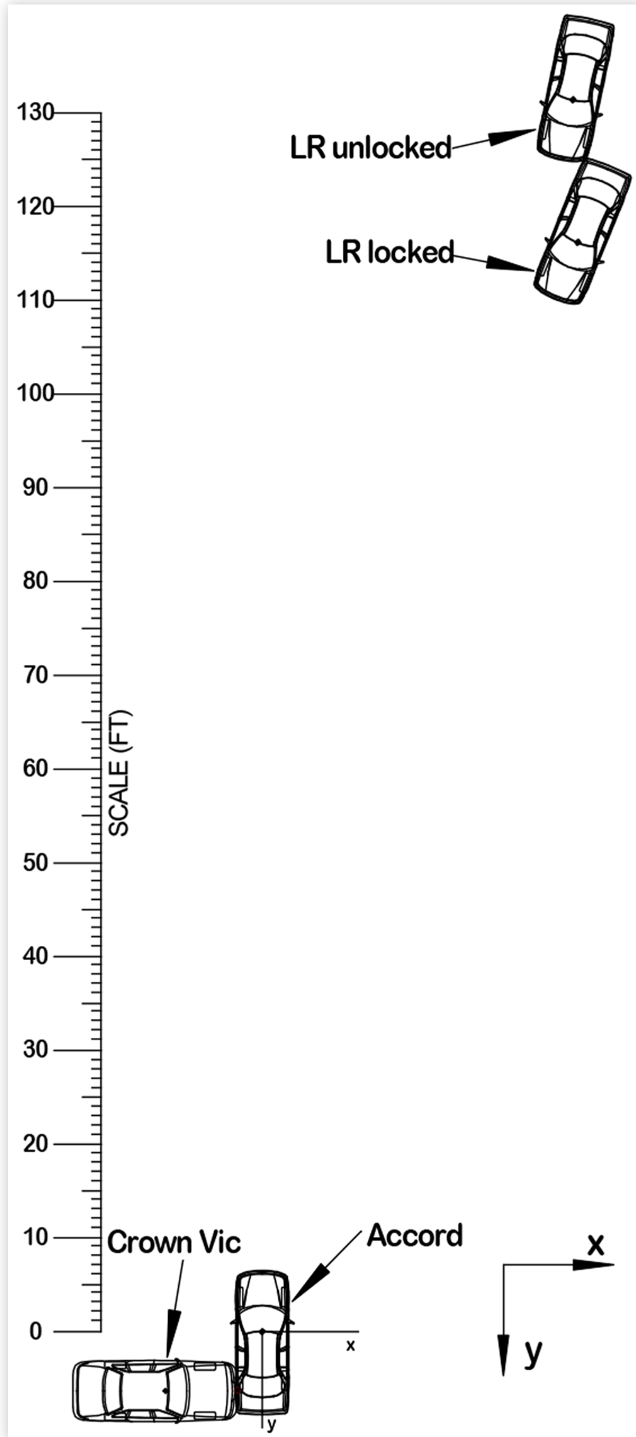
Looking at the nominal rest positions of these two conditions (see Figure 4) is something that a reconstructionist would likely do when faced with uncertainty as to whether the LR wheel was locked or not on the Accord in this situation. This comparison provides some insight into the behavior of the simulation program to the change in the singular condition. This comparison tells the reconstructionist that the condition of the LR wheel is consequential to the postimpact motion of the vehicle under these circumstances (as might be expected). It will be beneficial to have some understanding of the sensitivity of the model to various factors under these different conditions. The "various factors" just mentioned are those input parameters to the model that will be used by the reconstructionist to achieve a match between the simulation and the physical evidence, i.e. the "tuning knobs" that the reconstructionist will change in combination to produce the desired match. This sensitivity can be evaluated using DOE.

Figure 5 shows the 32 values of the y-coordinate response. Figure 6 shows the 32 values of the θ-coordinate response. (The data points are connected by a line not to illustrate a trend, but for ease of comparison of the data sets.)

A few general observations can be made regarding these three plots of the coordinate responses of the system for the two conditions:

- The similarity between the data show that the θ-coordinate response is relatively insensitive to the condition of the LR wheel (locked or unlocked). See Figure 6. This is also shown by the comparison of the nominal runs where the final angular orientations are nearly the same.
- The nature of the response data sets for the y-coordinate show that, for the variations of the factors in the study, the y-coordinate value will be greater for the unlocked condition than for the locked condition (see Figure 5). This difference is noticeable in the scale drawing of the nominal responses shown in Figure 4. The rest positions shown differ in the y-direction by 15.2 feet. Note that in this case, the vehicle traveled 15 feet farther for unlocked condition than the locked condition. The angular displacements are relatively close, consistent with the observation in the previous bullet.

FIGURE 4 Scale diagram showing the rest positions of the Accord for the left rear wheel locked and unlocked. All other parameters and conditions were identical. Both runs were done with VCRware. The impact position is shown for reference.



The results of the DOE analysis are shown in Figures 7, 8 and 9. The data are shown here using a "main effects"

FIGURE 5 The 32 values of the y-coordinate response with displacement on the Y axis and trial number on the X axis. (Trial 0 is the result for the nominal factor values.)

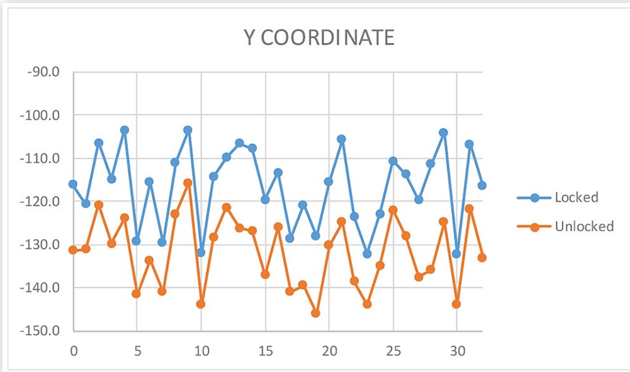


FIGURE 6 The 32 values of the θ-coordinate response with rotational displacement on the Y axis and trial number on the X axis.

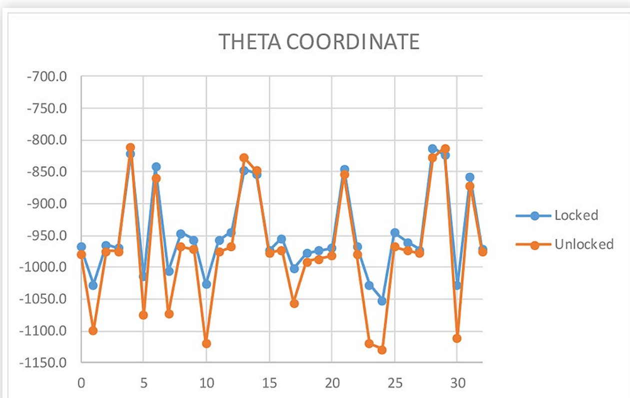
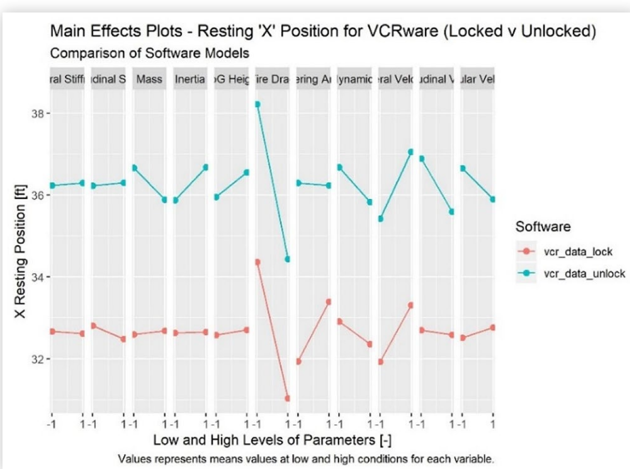


FIGURE 7 Main effects plot for x-coordinate response.



plot. A main effects plot for a given set of factors displays the response mean for each factor level. These two levels are connected by a line for visual evaluation. In the analysis here, each factor has a high value and a low value. Thus, the main effects plots for this analysis show the response

FIGURE 8 Main effects plot for y-coordinate response.

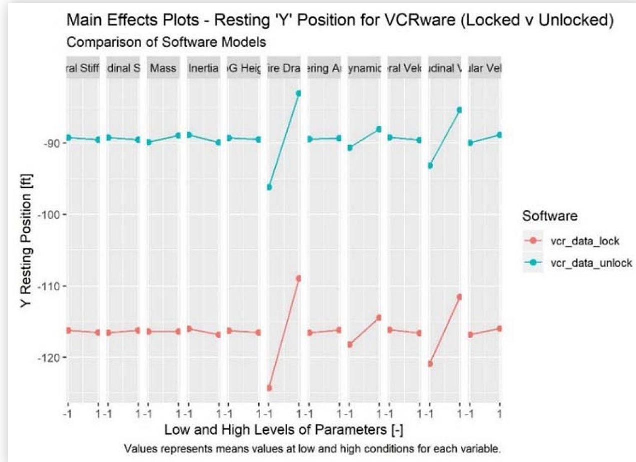
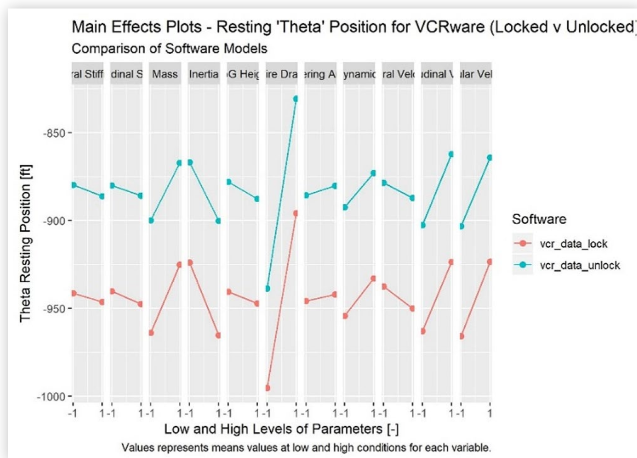


FIGURE 9 Main effects plot for θ-coordinate response.



means for the high and low values of each of the eleven factors (see Table 1).

Figure 7 shows the main effects plot for the results for the *x*-coordinate response. Figure 8 shows the main effects plot for the results for the *y*-coordinate response. Figure 9 shows the main effects plot for the results for the *θ*-coordinate response.

The main effects plots illustrate sensitivity to changes in a factor by the slope of the line connecting the mean value of the response at the high and low values of the factor. The direction of the slope also characterizes the nature of the response. If the slope is positive, the response increases when the value of the factor is increased (or changes from on to off as in the case of the aerodynamic forces). If the slope is negative, the opposite is true.

A number of observations can be made regarding these three plots of the coordinate responses of the system for the two conditions:

- The factor that both simulation processes are most sensitive to across all three response variables is the roadway frictional drag (tire_drag). This was expected based on prior work [1] and intuition.

- For the x-coordinate response variable, both the simulation processes are relatively insensitive to the lateral and longitudinal tire stiffnesses (lat_stf and long_stf).
- Both simulation processes show sensitivity to aerodynamic drag across all three response variables. The sensitivity changes sign for the x-coordinate where the vehicle will travel further in the x-direction when aerodynamic drag is not included. This is not intuitive but is borne out through data analysis.
- Simulation of both wheel conditions show sensitivity to the initial speeds, although the sensitivity is different between the three response variables and the three components of the initial speed.
- It is notable that the simulation processes are sensitive to the mass and inertia factors, but not in all cases. For instance, the y-coordinate response variable for both locked and unlocked conditions are relatively insensitive to these two factors. However, the x-coordinate response variable for the unlocked only shows sensitivity (locked does not) and for the θ-coordinate, both simulation processes show sensitivity to these two factors.

A distinct advantage of the DOE method for evaluating sensitivity is that the process inherently includes the effects of the interactions of factors included in the study.

Phase 2: Results of All Four Simulation Programs: A DOE analysis was conducted with all four of the simulation programs with the same condition for all four wheels i.e. the left rear wheel locked (due to damage) with the other three wheels assigned a nominal amount of drag consistent across the four programs. This analysis used the eleven factors and the high/low values as listed in Table 1. Every measure was taken to ensure that the values of the factors were kept the same when possible and as close as practical when the models differed with the definition of a parameter. Note that simulation model in EDSMAC4 does not accommodate aerodynamic drag whereas the other simulation programs do have this capability.

Significant Factors

Analysis of DOE results for significant model parameters was performed by developing regression models that included main effects and 2-factor interactions terms while noting that the two factor interaction terms are confounded with other 2-factor interactions. Significant factors (YES) were identified as those terms that exhibited a p-value less than 0.05, otherwise the factor or factor combination was listed as NO.

In addition to the Significant Model Terms plots illustrated above (Figures 10, 11 and 12), the effects of the factors on the response of the models as calculated by the DOE can also be evaluated using a Main Effects plot as was shown in the previous example. The three Main Effects plots, one for each of the response variables, are needed here to show this response.

Figure 13 is the Main Effects plot for the system response of the x-position. Figure 14 is the Main Effects plot for the system response of the y-position. Figure 15 is the Main Effects plot for the system response of the θ-position.

FIGURE 10 Comparison of significant factors for X-position for the four software models.

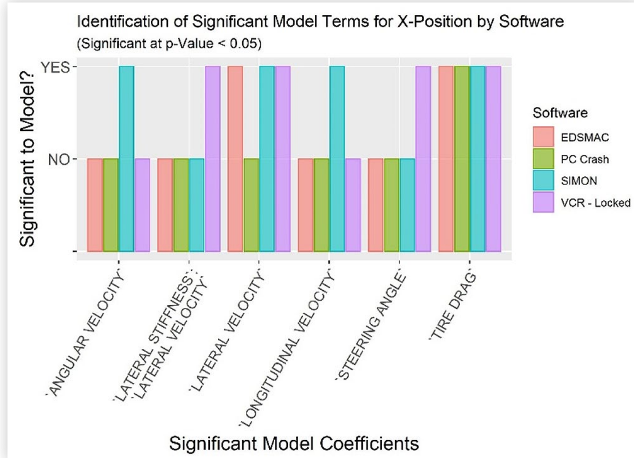


FIGURE 11 Comparison of significant factors for Y-position for the four software models.

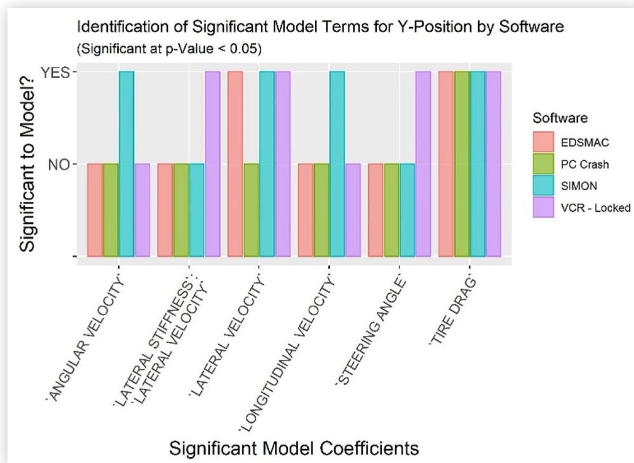


FIGURE 12 Comparison of significant factors for θ-position for the four software models.

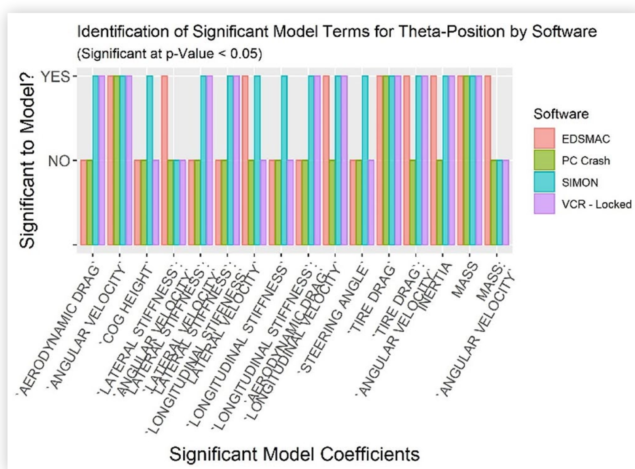


FIGURE 13 Main Effects plot for the x-position.

FIGURE 14 Main Effects plot for the y-position.

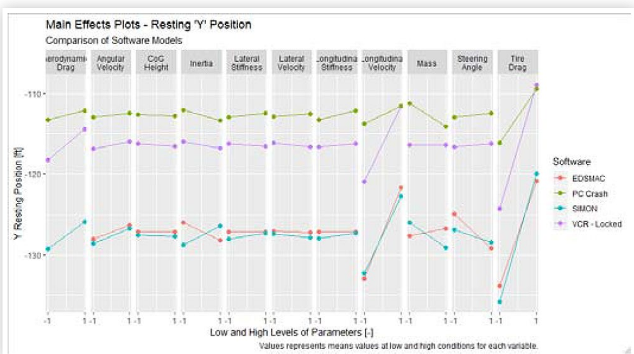


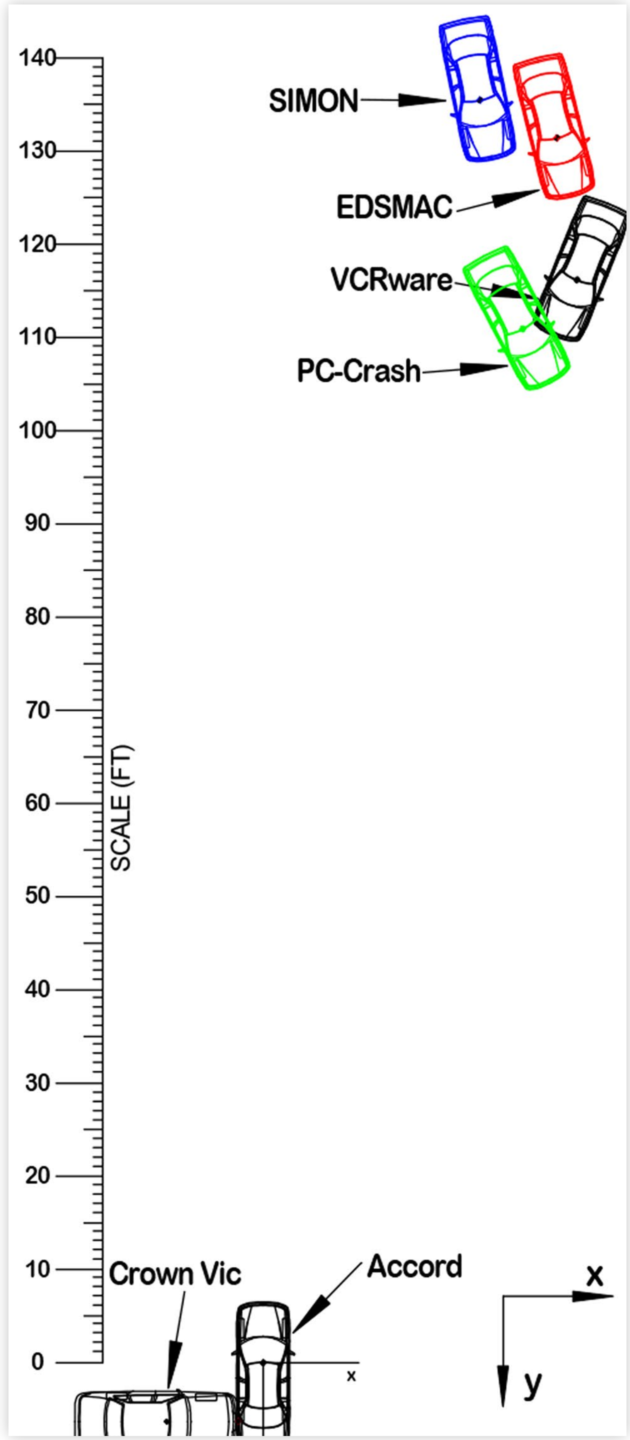
FIGURE 15 Main Effects for all plot for the θ-position.

In addition to the Main Effects plots and the Significant Model Terms plots, it is helpful to examine the rest positions of the vehicles on a scale diagram.

The nominal case for each of these four simulation programs is shown in Figure 16. The nominal case does not include aerodynamic drag.

In addition to the DOE providing insights into the sensitivity of the various simulation programs to the selected factors, the data can be used to evaluate the comparative behavior of the programs. The six scale diagrams shown in Figure 16 through Figure 21 show the rest positions calculated for each of the four simulation programs for the assigned run conditions (see Appendix B). Note that for each of these diagrams, the factors for each run are identical, or as near

FIGURE 16 Scale diagram showing the rest positions of the Accord for each of the four simulation programs with the left rear wheel locked for the nominal values. All other parameters and conditions were identical. The impact position is shown for reference.



identical as the analysts could achieve within program differences. Therefore, observations regarding the behavior of the simulation programs can be made. A subset of the total 32 runs (plus the nominal run) was selected as comparisons between all the runs would be very time consuming.

FIGURE 17 Rest position of the vehicles for each of the four software programs for Run 1.

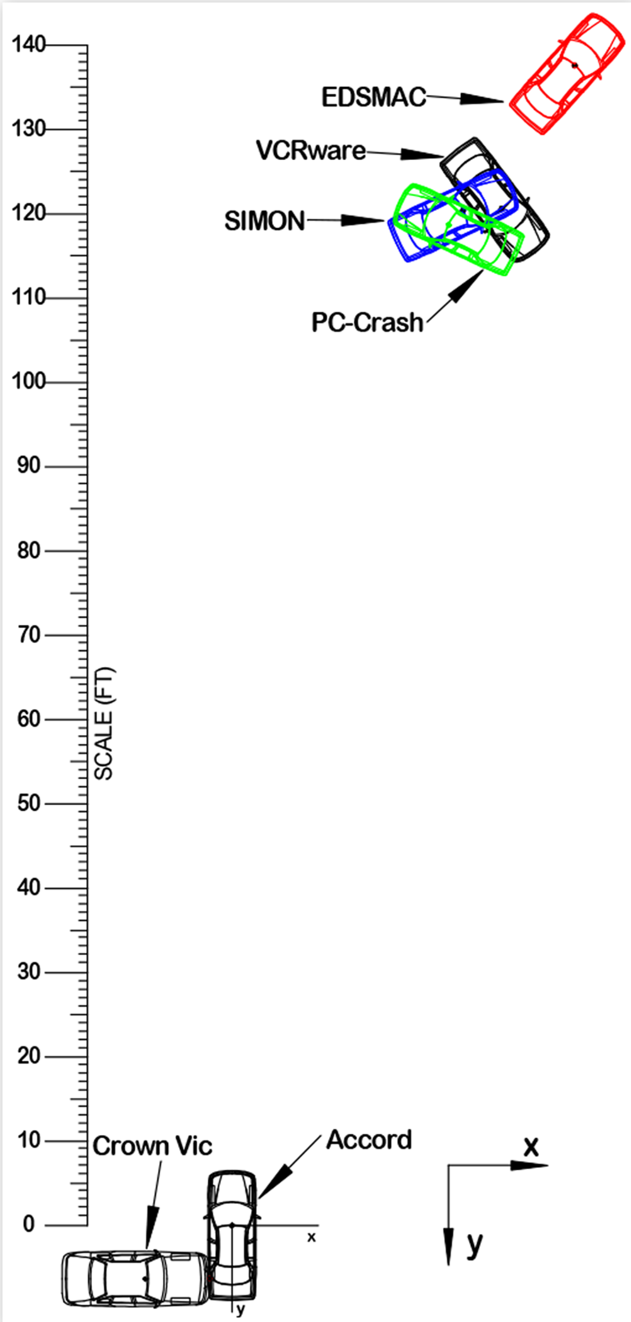
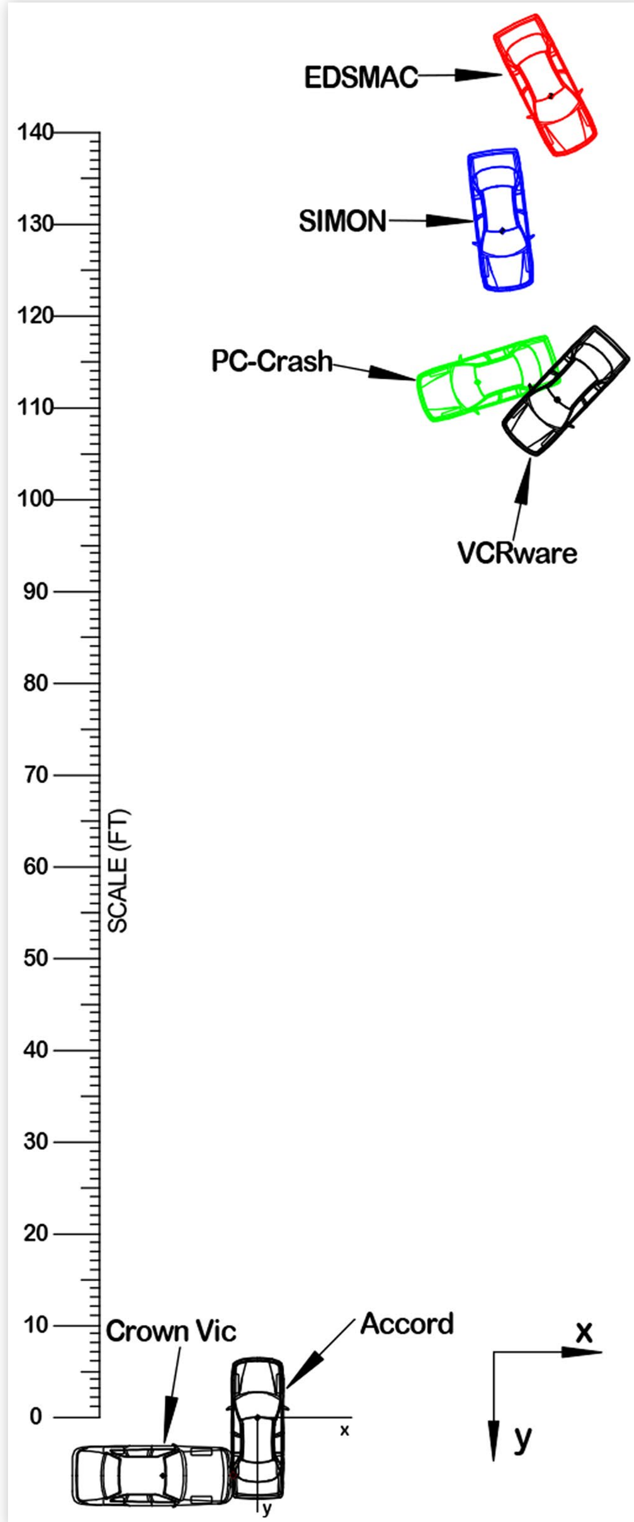


FIGURE 18 Rest position of the vehicles for each of the four software programs for Run 8.



Note that in all the cases EDSMAC4 does not incorporate aerodynamic drag. Of the trials examined here, Runs 1, 8 and 32 include aerodynamic forces. Runs 16 and 24 and the nominal case do not include aerodynamic forces.

OBSERVATIONS

- For the *x*- and *y*-positions, four single factors and one two-factor interaction term were significant. Tire-roadway drag was significant in all four models. Lateral velocity was significant to all but PC-Crash. Initial angular and longitudinal velocities were significant to only SIMON. The steering angle was significant to only VCRware. The two-factor interaction between lateral stiffness and lateral velocity was significant to only VCRware.

FIGURE 19 Rest position of the vehicles for each of the four software programs for Run 16.

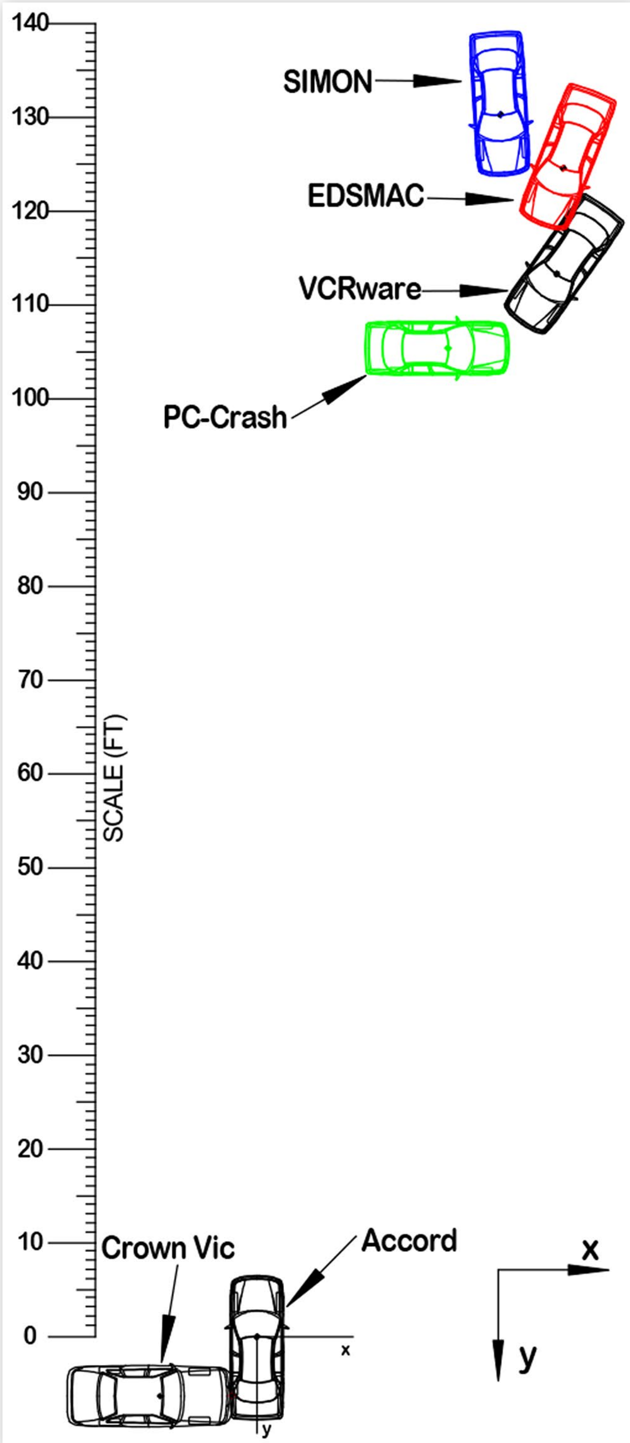
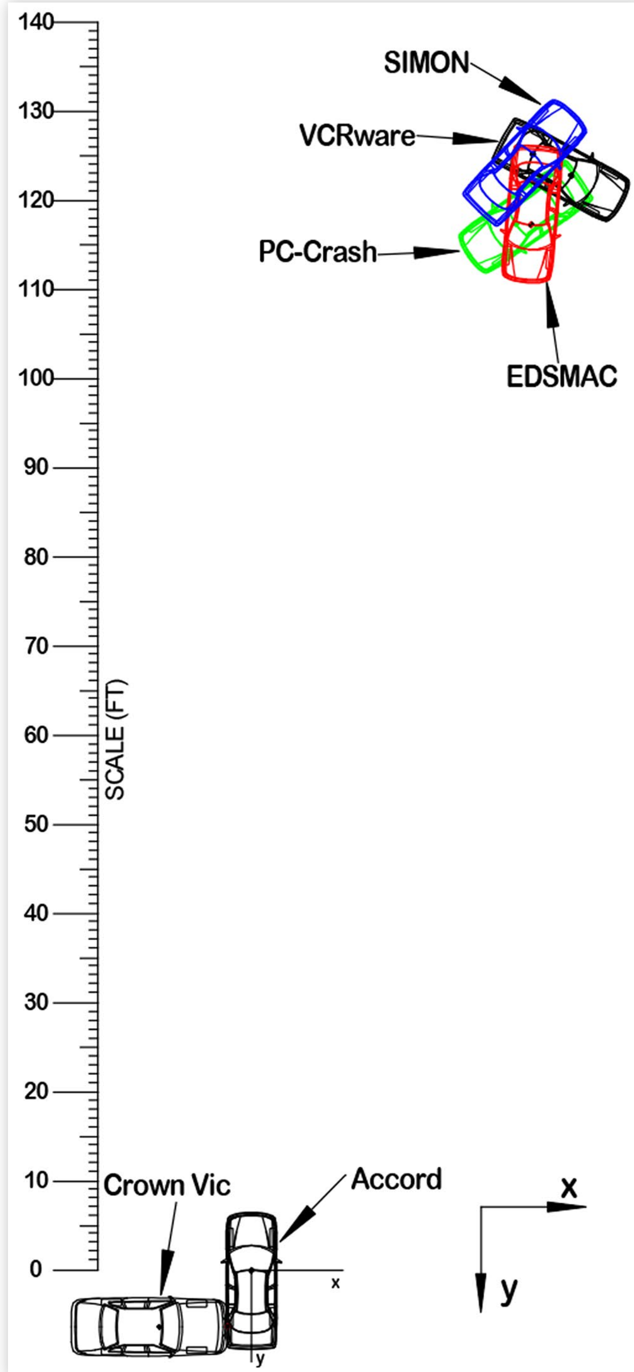
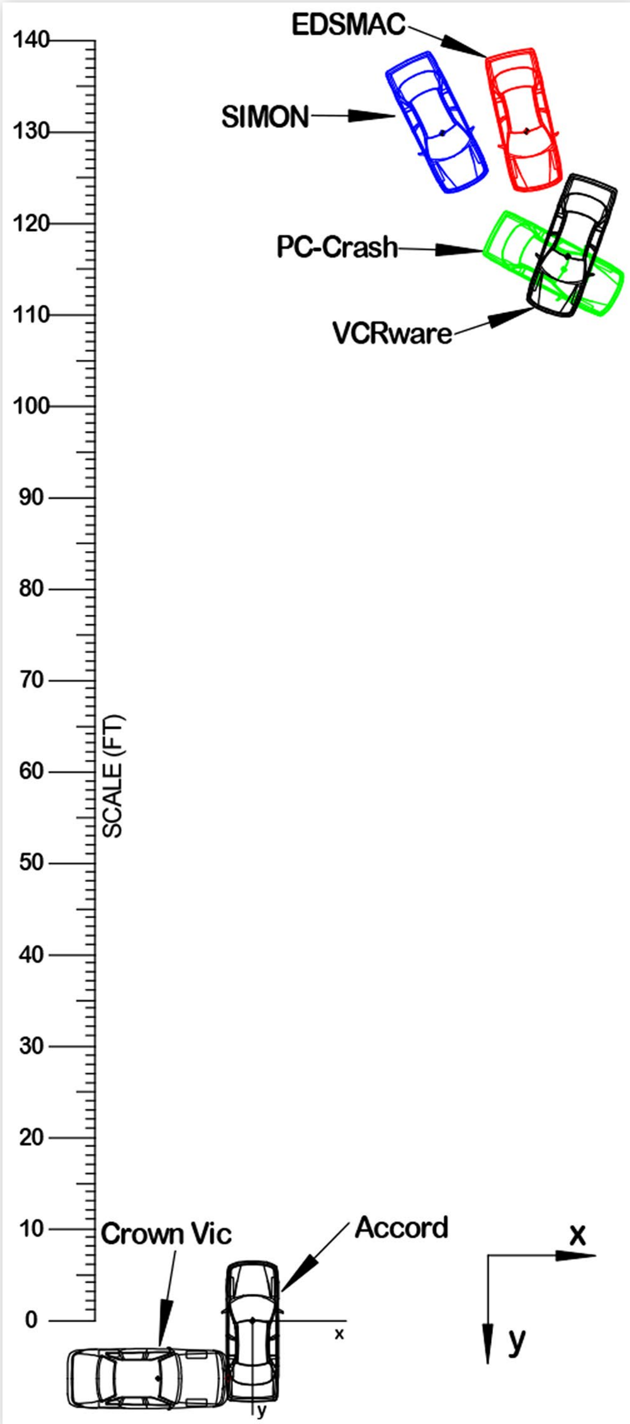


FIGURE 20 Rest position of the vehicles for each of the four software programs for Run 24.



- For the rotational displacement, ten single factors and six two-factor interaction terms were significant. Tire-roadway drag, mass, and initial angular velocity were significant to all four models. Rotational inertia was significant to all but PC-Crash. Aerodynamic drag was significant to SIMON and VCRware. Steering angle was only significant to SIMON.
- The main effects plots indicate all four models were most sensitive to tire-roadway drag.
- The main effects plot for the *x*-position show that VCRware and EDSMAC cluster together. VCRware and EDSMAC are nearly identically sensitive to lateral velocity and steering angle. PC-Crash is sensitive to changes in the CG height and longitudinal stiffness. SIMON is most sensitive to the changes in the initial speed conditions.

FIGURE 21 Rest position of the vehicles for each of the four software programs for Run 32.



- The main effects plot for the *y*-position show that EDSMAC and SIMON cluster together. EDSMAC and SIMON are nearly identically sensitive to longitudinal velocity.
- Sensitivities to parameters in opposite directions in the *x*-position include longitudinal velocity with PC-Crash. For the *y*-direction Inertia and Mass for SIMON and EDSMAC, though to a small degree.
- The rotational displacement was relatively insensitive to CG height, lateral velocity, and tire stiffnesses. The main effects plot for the rotational displacement also shows that PC-Crash produces rotational displacements consistently less than the other models. Note counterintuitively, that the translational displacements from PC-Crash are not noticeably different than the other three programs as shown in Figures 16 - 21. Steering angle had an opposite effect between SIMON and EDSMAC but to a small degree.
- The scale rest positions show that PC-Crash produces results for the *x*-direction displacement and y-direction displacement that are consistent with the other three programs.
- For five of the six cases evaluated here, the four programs tend to give translational displacement that are similar with Run 8 (Figure 18) showing the largest dispersion of the rest positions. The final angular orientations in some of the cases are similar (nominal, Run 8, Run 16 and Run 32) and dissimilar (Run 1, and Run 24).
- The rest positions and orientations of EDSMAC4 and SIMON closely track each other in translational displacement. The angular orientations of the rest positions also are very similar in five of the six cases, Run 24 being the outlier.
- In five of the six runs, the translational displacements of EDSMAC4 and SIMON are generally similar, with the exception being Run 1. The displacements in the *y*-direction for these two programs are the largest in four of the six cases, Runs 1 and 24 being the exceptions.

Discussion

The DOE analysis shows that these four simulation programs have different sensitivities to the eleven factors selected in the study. One common characteristic between the programs is that the tire-roadway frictional drag value was significant for all programs for all three response parameters. This should not be a surprise to reconstructionists who have used vehicle dynamics simulation programs. Generally, reconstructionists recognize that the frictional drag is an important parameter and include this parameter in reconstructions and in handling uncertainty.

The analysis shows that various interactions can also be significant. Interactions provide the reasoning for the trade-offs that are part of any reconstruction analysis. In this way, changing one input parameter with the intent of inducing a favorable change in one of the response parameters, often leads to an unfavorable change in one of the other response parameters. Faced with this common situation, reconstructionists typically aim to achieve a “best fit” in the analysis based on judgement that balances these competing responses. Use of optimization, such as implemented by PC-Crash, and least squares approaches can be helpful to the reconstructionist.

DOE analysis as presented here, has provided some interesting insights observed above into the behavior of these four simulation programs. These insights about the sensitivity of a simulation program, including factor interactions, and perhaps the identification of specific significant factors, might be useful to the reconstructionist. In these situations, it may be beneficial for the reconstructionist to run a "small" DOE, with perhaps four factors, to provide the reconstructionist with useful insights about the behavior of a program. Note that insights generated via a DOE analysis for one crash situation may not be applicable in another crash situation. Fortunately, a small DOE with a handful of factors typically can be easily run.

The authors do not intend that this DOE sensitivity method will become a day-to-day tool used by accident reconstructionists but rather a tool for understanding the sensitivity of their selected vehicle dynamics simulation program over a range of factors.

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Appendix A

Results of the planar impact mechanics (PIM) analysis for the impact between the 1991 Honda Accord and the 2005 Ford Crown Victoria used for the DOE analysis. Final Velocity values generated here were used as the nominal values for the speed factors in the DOE.

Analysis of a Planar Vehicle Collision

impact.xls
ver 3.3
9/18/2016

Un Conve

			HONDA Vehicle 1			FORD Vehicle 2
5280/3600	1.467		99.01	mass, m	lb-s²/ft	126.10
g	32.174	ft/s²	2000.00	inertia, I	ft-lb-s²	2970.59
			6.89	distance, d	ft	7.55
e	0.100		156.89	angle, ϕ	deg	0.00
μ (% μ₀)	100.0		-90.00	angle, θ	deg	0.00
μ	-0.789					
μ₀	-0.789			INITIAL Velocity		
Γ	0.000	deg		v	kph	
			0.00	v_x	ft/s	73.363
mbar	55.464		73.363	v_y	ft/s	0.00
k_1^2	20.199	ft^2	0.00	ω	deg/sec	0.00
k_2^2	23.557	ft^2	73.36	v	ft/s	73.36
q	0.402		0.00	v_n	ft/s	73.36
v_{rn}	73.363	ft/s	73.36	v_t	ft/s	0.00
v_{tn}	-73.363	ft/s	0.00	v_{cn}	ft/s	73.36
r	-1.000		73.36	v_{ct}	ft/s	0.00
η_1	-90.000	deg				
η_2	0.000	deg		FINAL Velocity		
d_a	0.000	ft	Vehicle 1			Vehicle 2
d_b	7.546	ft	18.17	V_x	ft/s	59.10
d_c	6.337	ft	59.04	V_y	ft/s	11.25
d_d	2.704	ft	436.43	Ω	deg/sec	206.45
d_e	8.469	ft	61.77	V	ft/s	60.16
d_f	5.951	ft	18.17	V_n	ft/s	59.10
A	2.114		59.04	V_t	ft/s	11.25
B	0.475		66.44	V_{cn}	ft/s	59.10
C	1.266		38.44	V_{ct}	ft/s	38.44
D	2.266					

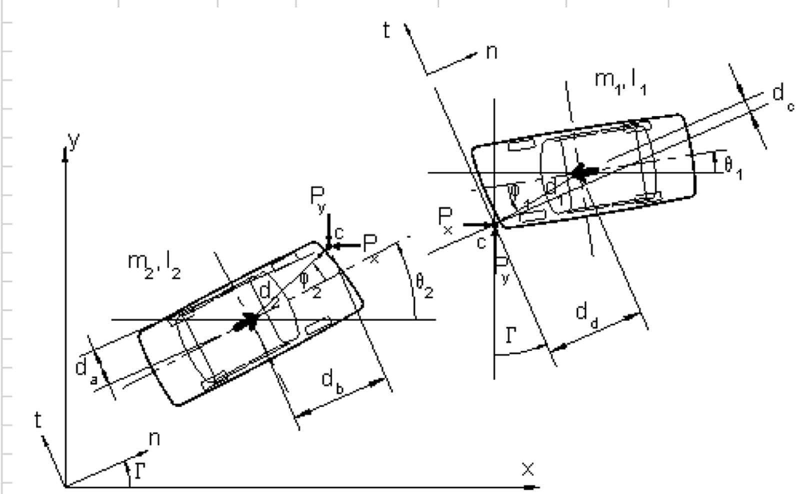
	Initial speeds	
Vehicle 1		Vehicle 2
50.0	mph	50.0
	Final speeds	
Vehicle 1		Vehicle 2
42.1	mph	41.0
	|ΔV|	
Vehicle 1		Vehicle 2
15.8	mph	12.4
23.1	ft/s	18.2

System Kinetic Energy, ft-lb		
Initial	605,799.9	
Final	494,385.3	
Loss	111,414.6	18.4%
Normal (Crush) Energy Loss:		
59,382.3	9.8%	
Tangential Energy Loss:		
52,032.3	8.6%	
Total System Energy Loss		
111,414.6	18.4%	

	Impulses, lb-s	
P_x	P_y	P
1798.7	-1418.5	2290.7
P_n	P_t	P
1798.7	-1418.5	2290.7

	PDOF, deg	
Vehicle 1		Vehicle 2
-51.7		38.3

	|ΔV| Components, mph	
Vehicle 1		Vehicle 2
12.39	$\|\Delta V_{lat}\|$	7.67
9.77	$\|\Delta V_{long}\|$	9.73



Brach Engineering
VCRware™
Vehicle Crash Reconstruction Software
www.brachengineering.com

Appendix B

The DOE structure used in the analysis with 11 factors, each at two levels, and 32 trials.

Trial	Lateral Stiffness	Long Stiffness	Weight	Yaw Inertia	CG Height	Roadway Drag	Steering Angle	Aero Drag	Lateral Speed	Long Speed	Angular Speed
1	-	-	-	+	-	-	+	+	-	-	+
2	+	-	-	+	+	+	-	-	-	-	+
3	+	+	-	-	+	-	-	+	+	-	-
4	+	-	-	-	+	+	+	+	-	-	-
5	-	-	-	+	+	-	+	+	+	+	-
6	+	+	+	-	+	+	-	-	+	+	-
7	+	-	+	+	+	-	-	+	-	+	+
8	+	+	+	+	+	+	+	+	+	+	+
9	-	+	-	+	-	+	-	+	+	-	+
10	-	-	-	-	+	-	-	-	+	+	+
11	-	-	+	+	-	+	+	-	-	+	+
12	-	+	-	+	+	+	-	+	-	+	-
13	-	+	-	-	-	+	+	-	+	-	-
14	-	-	+	+	+	+	+	-	+	-	-
15	-	-	-	-	-	-	-	-	-	-	-
16	-	+	-	-	+	+	+	-	-	+	+
17	+	+	-	-	-	-	-	+	-	+	+
18	+	-	+	-	-	-	+	-	+	-	+
19	+	-	+	-	+	-	+	-	-	+	-
20	-	+	+	-	+	-	+	+	-	-	+
21	-	-	+	-	+	+	-	+	+	-	+
22	-	+	+	-	-	-	+	+	+	+	-
23	-	+	+	+	-	-	-	-	+	+	+
24	+	+	-	+	+	-	+	-	+	-	+
25	+	-	-	-	-	+	+	+	+	+	+
26	+	-	-	+	-	+	-	-	+	+	-
27	-	+	+	+	+	-	-	-	-	-	-
28	-	-	+	-	-	+	-	+	-	+	-
29	+	+	+	+	-	+	+	+	-	-	-
30	+	+	-	+	-	-	+	-	-	+	-
31	+	+	+	-	-	+	+	-	-	-	+
32	+	-	+	+	-	-	-	+	+	-	-

Appendix C - HVE EDSMAC4 Nominal Run Inputs

```
DOE runs 2018                                              Thu 10/31/19 06:26:17
Accident History-EDSMAC4, Accord nominal                   HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                  PAGE 1


                              ----- ACCIDENT HISTORY -----

                         time       X       Y      PSI      Vtot    U      V   Yaw Vel
                        (sec)     (ft)    (ft)    (deg)    (mph)  (mph)  (mph) (deg/sec)
-Start of Simulation-
       Accord nominal   0.0000     0.0     0.0    -90.0     42.1   40.3   12.4 -436.4


--- At Final/Rest ---
       Accord nominal   5.2530    31.6  -131.4 -1004.1      0.0    0.0    0.0    0.0



DOE runs 2018                                              Thu 10/31/19 06:26:20
Driver Controls-EDSMAC4, Accord nominal                    HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                  PAGE 1


                 ----------DRIVER CONTROL TABLES ------------

          Driver Controls for Accord nominal
            Steer Table:
                         Steer
              Time       Angle
             (sec)       (deg)
            0.0000        0.00

            Throttle Table:
              Time        R/F         L/F         R/R         L/R
             (sec)     (%/100)     (%/100)     (%/100)     (%/100)
            0.0000        0.00        0.00        0.00        0.00

            Brake Table:
              Time        R/F         L/F         R/R         L/R
             (sec)        (lb)        (lb)        (lb)        (lb)
            0.0000      -97.22      -97.22       -4.35   -10000.00
```

```
DOE runs 2018                                          Thu 10/31/19 06:26:22
Environment Data-EDSMAC4, Accord nominal              HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1


                         GENERAL ENVIRONMENT DATA

              Environment Name:               Untitled Environment
                          Date:                           08/17/16
                          Time:                               1200
   Ambient Temperature (Farenheit):                          68.00
          Ambient Pressure (in-Hg):                          29.92
       Gravity Constant (in/sec^2):                         386.40


                       3-D ENVIRONMENT TERRAIN DATA

         3-D Geometry Filename:                  ProvingGround.h3d
        Total Number of Polygons:                               10
                GetSurfaceInfo:      From Previous Polygon, Sorted
   Minimum Terrain Elevation (ft):                            0.01
   Maximum Terrain Elevation (ft):                            0.00

        Number of Water Polygons: None

         Number of Curb Polygons: None

  Number of Friction Zone Polygons: None

         Number of Road Polygons: 10
      Start     Friction       X,min      X,max      Y,min      Y,max
        ID    Multiplier        (ft)       (ft)       (ft)       (ft)
         0       1.000        -490.2     2009.8     -504.9       95.1
         2       0.550       -1000.0     3000.0    -1000.0      600.0
```

```
DOE runs 2018                                          Thu 10/31/19 06:26:24
Event Data-EDSMAC4, Accord nominal                    HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1

                              STATIC VEHICLE LOADS

         Vehicle Axle Loads (lb):       Empty

                   Accord nominal
                          Axle 1:       1935.4
                          Axle 2:       1250.6
                          --------------------
                           Total:       3186.0

                               VEHICLE EVENT DATA

     Event Data for Accord nominal:

       Payload Information -- (No Payloads)

     Accelerometer Information -- (No Accelerometers)

       Event Wheel Data, Wheels & Tires, Front Axle --
         Wheel Displacements -- (No Displaced Wheels)

         Tire Blow-outs -- (No Tire Blow-outs)

         Tire Hydroplaning -- (No Hydroplaning at this axle)

       Event Wheel Data, Second Axle --
         Wheel Displacements -- (No Displaced Wheels)

         Tire Blow-outs -- (No Tire Blow-outs)

         Tire Hydroplaning -- (No Hydroplaning at this axle)


DOE runs 2018                                          Thu 10/31/19 06:26:27
Messages-EDSMAC4, Accord nominal                      HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1

                              MESSAGES

                             No Messages
```

```
DOE runs 2018                                              Thu 10/31/19 06:26:29
Program Data-EDSMAC4, Accord nominal                      HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                  PAGE 1


               GENERAL PROGRAM INFORMATION

   Execution Information ---
                 HVE Version:      HVE 2018 Version 14.00
             EDSMAC4 Version:                        8.30
           Date of Execution:                    Thu 10/31/19
           Time of Execution:                    06:23:59

         Program Options ---
             Dimension Basis:               Sprung Mass CG
          Hydroplaning Option:                        Off

     Simulation Controls ---
    Max Simulation Time (sec):                    12.0000
     Collision Phase dt (sec):                     0.0010
    Separation Phase dt (sec):                     0.0010
    Trajectory Phase dt (sec):                     0.0010
         Output Interval (sec):                    0.0010
         Linear Term Vel (mph):                      0.25
   Angular Term Vel (deg/sec):                       5.00
```

DOE runs 2018 Thu 10/31/19 06:26:31
References-EDSMAC4, Accord nominal HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc. PAGE 1

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```
DOE runs 2018                                                 Thu 10/31/19 06:26:33
Vehicle Data-EDSMAC4, Accord nominal                          HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                      PAGE 1


-------------------- VEHICLE DATA --------------------

                   Vehicle Name:         Accord nominal
                   Vehicle Type:          Passenger Car
         Vehicle Version Number:                V  8.20
       Body Overall Length (in):                 184.00
          Body CG To Front (in):                  77.00
           Body CG To Rear (in):                -107.00
        Body Overall Width (in):                  67.90
              CG Elevation (in):                  21.13
               Roll Couple Dist:                   0.66
              Total Weight (lb):                3186.00
       Total Mass (lb-sec^2/in):                   8.25
  Yaw Inertia Tot (lb-sec^2-in):               24000.00
 Yaw Inertia Sprg (lb-sec^2-in):               22349.58
        3-D Geometry Filename:  PCHondaAccord924Dr.h3d
            Number of Vertices:                       0
    Number of Damaged Vertices:                       0

                                  A Stiff    B Stiff
                                  (lb/in)   (lb/in^2)
                      Front End:    335.6       118.3
                     Right Side:    246.0        86.0
                       Back End:    239.0       110.0
                      Left Side:    246.0        86.0


----------------- WHEEL AND TIRE DATA ----------------

   Wheels & Tires, Front Axle --      Right        Left
         Wheel Locn (in) - x:         42.00       42.00
                           y:         29.05      -29.05
                           z:          9.02        9.02
                   Tire Name:       Generic     Generic
                   Tire Size:    P195/60R15  P195/60R15
                Slide Mu (*):          0.70        0.70
     Vel Dependence (sec/in):       0.00000     0.00000
   Cornering Stiffness (lb/deg):     226.90      226.90

                 Second Axle --       Right        Left
         Wheel Locn (in) - x:        -65.00      -65.00
                           y:         29.15      -29.15
                           z:          9.02        9.02
                   Tire Name:       Generic     Generic
                   Tire Size:    P195/60R15  P195/60R15
                Slide Mu (*):          0.70        0.70
     Vel Dependence (sec/in):       0.00000     0.00000
   Cornering Stiffness (lb/deg):     226.90      226.90


----------------- STEERING SYSTEM DATA ---------------


                    First Axle:              Steerable
  Steering Gear Ratio (deg/deg):                 16.62
     Ackermann Steering Option:                     On

                   Second Axle:          Not Steerable
```

Appendix D - HVE Simon Nominal Run Inputs

```
Untitled                                                      Fri 11/01/19 11:28:27
Accident History-SIMON, Event                                HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                     PAGE 1


                              ----- ACCIDENT HISTORY -----

                          time        X        Y  Heading      Vtot     U       V   Yaw Vel
                         (sec)      (ft)     (ft)   (deg)      (mph)  (mph)   (mph)(deg/sec)
-Start of Simulation-
               Accord    0.0000     -0.0     -0.0    -90.0      42.1   40.3    12.4 -436.4


--- At Final/Rest ---
               Accord    5.5451     23.3   -135.4 -1001.6       0.0    0.0     0.0     0.0



Untitled                                                      Fri 11/01/19 11:28:39
Driver Controls-SIMON, Event                                 HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                     PAGE 1


                -------------- DRIVER CONTROLS -----------------

   Driver Controls for: Accord


                      DRIVER CONTROL TABLES (OPEN-LOOP)

     Steer Table:
                        Axle 1         Axle 1
           Time          Right           Left
          (sec)          (deg)          (deg)
         0.0000           0.00           0.00

     Brake Table:
                        Axle 1         Axle 1         Axle 2         Axle 2
           Time          Right           Left          Right           Left
          (sec)        (%/100)        (%/100)        (%/100)        (%/100)
         0.0000           0.00           0.00           0.00           1.00

     Throttle Table:
                      Throttle
           Time       Position
          (sec)        (%/100)
         0.0000           0.00

     Differential Shift Table: (No Differential Table)
```

```
Untitled                                              Fri 11/01/19 11:28:45
Environment Data-SIMON, Event                         HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1


                      GENERAL ENVIRONMENT DATA

                  Environment Name:               Untitled Environment
                              Date:                           08/10/18
                              Time:                               1200
   Ambient Temperature (Farenheit):                              68.00
          Ambient Pressure (in-Hg):                              29.92
             Air Density (lb/ft^3):                             0.0752
                  Wind Speed (mph):                               0.00
              Wind Direction (deg):                               0.00
       Gravity Constant (in/sec^2):                             386.40


                    3-D ENVIRONMENT TERRAIN DATA

              3-D Terrain Filename:                               None
          Total Number of Polygons:                                  2
                    GetSurfaceInfo:      From Previous Polygon, Sorted
    Minimum Terrain Elevation (ft):                               0.00
    Maximum Terrain Elevation (ft):                               0.00

          Number of Water Polygons: None

           Number of Curb Polygons: None

  Number of Friction Zone Polygons: None

           Number of Road Polygons: 2
       Start    Friction        X,min      X,max      Y,min      Y,max
         ID    Multiplier        (ft)       (ft)       (ft)       (ft)
          0       0.790        -500.0      500.0     -500.0      500.0
```

```
Untitled                                                   Fri 11/01/19 11:28:48
Event Data-SIMON, Event                                    HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                  PAGE 1

                              STATIC VEHICLE LOADS

         Vehicle Axle Loads (lb):       Empty

                          Accord
                         Axle 1:        1864.5
                         Axle 2:        1321.5
                         --------------------
                          Total:        3186.0

                               VEHICLE EVENT DATA

     Event Data for Accord:

       Payload Information: (No Payloads)

       Accelerometer Information: (No Accelerometers)

       Collision Pulse Information: (No Collision Pulse)

       Event Wheel Data, First Axle ---

         Wheel Damage: (No Damaged Wheels on this axle)

         Brake Temp/Adjustment Data: (Generic Brakes; No Data)

         Brake Failure Data: (No Failed Brakes on this axle)

         Tire Blow-outs: (No Tire Blow-outs on this axle)

         Tire-Terrain Model Data:
                                               Right Side        Left Side
                                               ----------        ----------
                     Tire-Terrain Model:            Point             Point

         Tire Hydroplaning: (No Hydroplaning at this axle)

       Event Wheel Data, Second Axle ---

         Wheel Damage: (No Damaged Wheels on this axle)

         Brake Temp/Adjustment Data: (Generic Brakes; No Data)

         Brake Failure Data: (No Failed Brakes on this axle)

         Tire Blow-outs: (No Tire Blow-outs on this axle)

         Tire-Terrain Model Data:
                                               Right Side        Left Side
                                               ----------        ----------
                     Tire-Terrain Model:            Point             Point

         Tire Hydroplaning: (No Hydroplaning at this axle)
```

```
Untitled                                              Fri 11/01/19 11:28:52
Messages-SIMON, Event                                 HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1

                              MESSAGES

                             No Messages
```

```
Untitled                                              Fri 11/01/19 11:28:56
Program Data-SIMON, Event                             HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                              PAGE 1


                        GENERAL PROGRAM INFORMATION

   Execution Information ---
                       HVE Version:            HVE 2018 Version 14.00
                     SIMON Version:                              5.00
                 Date of Execution:                      Thu 02/28/19
                 Time of Execution:                          13:32:58

     Simulation Controls ---
                Integration Method:                Fixed Runge-Kutta
     Maximum Simulation Time (sec):                            6.0000
        Integration Timestep (sec):                            0.0025
             Output Interval (sec):                            0.0100
              Linear Term Vel (mph):                             2.00
        Angular Term Vel (deg/sec):                              5.00

     Calculation Options ---
                    GetSurfaceInfo:      From Previous Polygon, Sorted
                 Tire Model Method:            Semi-empirical, Vers. 2
            Steer Degree Of Freedom:                               Off
               Articulation Option:                                 On
                      DyMESH Option:                               Off
                Hydroplaning Option:                               Off
```

Untitled Fri 11/01/19 11:28:58
References-SIMON, Event HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc. PAGE 1

--------- TECHNICAL REFERENCES ---------

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```
Untitled                                                Fri 11/01/19 11:29:00
Vehicle Data-SIMON, Event                               HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                               PAGE 1

                              VEHICLE DATA

     General Information ---
                              Vehicle Name:          Accord
                              Vehicle Type:          Passenger Car
                              Vehicle Make:          Honda
                             Vehicle Model:          Accord
                              Vehicle Year:          1990-1993
                        Vehicle Body Style:          4-Door
                                Version No:   V  8.20 (RCS $Revision: 2.3
                           Number of Axles:          2
                           Driver Location:          Left Side
                           Engine Location:          Front Engine
                             Drive Axle(s):          Axle 1

     Steady-State Handling Properties ---
           Total Understeer Gradient (deg/g):        1.23
          Steering Wheel Sensitivity (deg/g):        55.83
                       Roll Gradient (deg/g):        2.64
       Roll Couple Distribution, F/R (%/100):        0.66
            Weight Distribution, F/R (%/100):        0.59
             Static Weight, Front Tires (lb):        1864.45
              Static Weight, Rear Tires (lb):        1321.55

     Sprung Mass Dimensional Data ---
                         Overall Length (in):        184.00
                          Overall Width (in):        67.90
                         Overall Height (in):        54.15
                       Ground Clearance (in):        9.15
                              Wheelbase (in):        107.04
                       CG to Front Axle (in):        43.90
                        CG to Back Axle (in):        -63.14
                              CG Height (in):        21.62
                         Front Overhang (in):        35.00
                          Rear Overhang (in):        41.96

     Sprung Mass Inertial Data ---
                           Total Weight (lb):        3186.00
                          Sprung Weight (lb):        3021.55
                   Sprung Mass (lb-sec^2/in):        7.82
Sprg Mass Rot Inertia (lb-sec^2-in) - Roll:          3123.27
                                       Pitch:        22782.37
                                         Yaw:        22369.11
                                  XZ Product:        0.00

     Sprung Mass Aerodynamic Parameters ---
                 Surface Name:
             Drag Coefficient:
      Proj. Surface Area (in^2):
   Center of Pressure (in) - x:
                             y:
                             z:

     Steering System Parameters ---

                                  First Axle:        Steerable
               Steering Gear Ratio (deg/deg):        16.62
                   Ackermann Steering Option:        On

                                       Right Side        Left Side
                                       ----------        ----------
                       Caster (deg):        3.00              3.00
```

```
Untitled                                                 Fri 11/01/19 11:29:00
Vehicle Data-SIMON, Event                               HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                PAGE 2
                Inclination Angle (deg):           6.83            6.83
                   Steering Offset (in):           0.17            0.17
                  Stub Axle Length (in):           1.71            1.71
      Initial Steer Axis Coord (in) - x:          43.90           43.90
                                      y:          27.33          -27.33
                                      z:           9.51            9.51

                             Second Axle:          Not Steerable

     Drivetrain Parameters ---
                         Engine Description:   1.6L Inline 4, 5-speed manual
                         Maximum Power (HP):               142
                     Maximum Torque (ft-lb):               136
                Transmission Forward Speeds:                5
                        Differential Speeds:                1

   Wide-open Throttle, Speed (RPM):    500   1300   3800   4000   4500   5200   5800   6500
                        Power (HP):      6     30     98    103    115    125    127    142
                    Torque (ft-lb):     65    120    136    135    134    126    115    115

      Closed Throttle, Speed (RPM):    500   2000   3000   4000   6500
                        Power (HP):     -1     -6    -15    -26    -72
                    Torque (ft-lb):     -6    -17    -25    -34    -58

                Transmission Type: Manual

                Transmission Gear:   Rev    1st    2nd    3rd    4th    5th
                  Numerical Ratio: -3.00   3.31   1.81   1.19   0.87   0.69

          Differential Gear Ratio:  4.060

     Electronic Stability Systems Properties ---

                          (No ESS Systems Installed.)

     Wheel Location Information, First Axle ---
                                             Right Side        Left Side
                                             ----------       ----------
     Initial Wheel Coordinates (in) - x:          43.90           43.90
                                      y:          29.04          -29.04
                                      z:           9.51            9.51

     Suspension Information, First Axle ---
                            Suspension Type:         Independent
        Auxiliary Roll Stiffness (in-lb/deg):             5775.14

                                             Right Side        Left Side
                                             ----------       ----------
                      Wheel Rate (lb/in):        110.90          110.90
             Viscous Damping (lb-sec/in):          8.80            8.80
                   Coulomb Friction (lb):         50.00           50.00
             Friction Null Band (in/sec):          5.00            5.00
          Deflection to Jounce Stop (in):         -4.00           -4.00
                  Stop Linear Rate (lb/in):      300.00          300.00
                Stop Cubic Rate (lb/in^3):       600.00          600.00
                Stop Energy Ratio (%/100):         0.50            0.50
         Deflection to Rebound Stop (in):          4.00            4.00
                  Stop Linear Rate (lb/in):      300.00          300.00
                Stop Cubic Rate (lb/in^3):       600.00          600.00
                Stop Energy Ratio (%/100):         0.50            0.50
             Roll Steer Const. Coef (deg):         0.00            0.00
          Roll Steer Linear Coef (deg/in):         0.00            0.00
     Roll Steer Quadratic Coef (deg/in):           0.00            0.00
```

Untitled Fri 11/01/19 11:29:00
Vehicle Data-SIMON, Event HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc. PAGE 3

Roll Steer Cubic Coef (deg/in): 0.00 0.00

Camber and Half-track Tables

-------- Right Side -------			-------- Left Side --------		
Susp Defl (in)	Camber (deg)	1/2-track Change (in)	Susp Defl (in)	Camber (deg)	1/2-track Change (in)
-4.00	0.00	0.00	-4.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	4.00	0.00	0.00

Tire Information, First Axle ---

	Right Side	Left Side
Tire Name:	Generic	Generic
Tire Manufacturer:	Generic	Generic
Tire Model:	Generic	Generic
Tire Size:	P195/60R15	P195/60R15
Version No:	V 5.20	V 5.20
Unloaded Radius (in):	12.10	12.10
Static Loaded Radius (in):	11.49	11.49
Nominal Width (in):	7.68	7.68
Tread Width (in):	6.14	6.14
Init. Radial Stiffness (lb/in/tire):	1506.33	1506.33
2nd Radial Stiffness (lb/in/tire):	15063.30	15063.30
Defl. @ 2nd Stiffness (in):	3.68	3.68
Max Deflection (in):	4.61	4.61
Rebound Energy Ratio (%/100):	1.00	1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in/	7.90	7.90
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in	3.89	3.89
Weight (Tire+Whl+Brk, lb/tire):	41.11	41.11
Roll Resistance Const:	0.01	0.01
Roll Resististance Linear Coef (sec/in):	0.00	0.00
Min Fz For Skidmark (lb):	308.00	308.00
Pneumatic Trail (in):	-0.86	-0.86

Cornering Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	607.3	1230.1	1845.7	607.3	1230.1	1845.7
Speeds (in/sec):	528.0			528.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	226.9	226.9	226.9	226.9	226.9	226.9

Camber Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	613.2	1235.7	1856.8	613.2	1235.7	1856.8
Speeds (in/sec):	528.0			528.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	5.0	12.5	19.2	5.0	12.5	19.2

Tire Friction Table:	Right Side			Left Side		
Loads (lb):	616.0	1229.0	1842.0	616.0	1229.0	1842.0
Speeds (in/sec):	528.0			528.0		
Speed No. 1, Load No.:	1	2	3	1	2	3
Peak Mu:	0.9810	0.9890	0.9940	0.9810	0.9890	0.9940
Slide Mu:	0.8660	0.7560	0.6750	0.8660	0.7560	0.6750
Slip @ Peak Mu (%/100):	0.2440	0.1680	0.1460	0.2440	0.1680	0.1460
Long. Stiffness (lb/slip):	10000.0	10000.0	10000.0	10000.0	10000.0	10000.0

Brake Information, First Axle ---

```
Untitled                                                   Fri 11/01/19 11:29:00
Vehicle Data-SIMON, Event                                 HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                  PAGE 4
                                              Right Side        Left Side
                                              ----------        ----------
                     Brake Assembly Type:   Generic Brake     Generic Brake
                     Brake Time Lag (sec):       0.0000            0.0000
                    Brake Time Rise (sec):       0.0000            0.0000
                    Pushout Pressure (psi):        0.00              0.00
 Nominal Brake Torque Ratio (in-lb/psi):          22.96             22.96

     Wheel Location Information, Second Axle ---
                                              Right Side        Left Side
                                              ----------        ----------
     Initial Wheel Coordinates (in) - x:         -63.14            -63.14
                                      y:          29.04            -29.04
                                      z:           9.51              9.51

     Suspension Information, Second Axle ---
                             Suspension Type:        Independent
        Auxiliary Roll Stiffness (in-lb/deg):               0.00

                                              Right Side        Left Side
                                              ----------        ----------
                        Wheel Rate (lb/in):      105.70            105.70
               Viscous Damping (lb-sec/in):        6.90              6.90
                     Coulomb Friction (lb):       50.00             50.00
              Friction Null Band (in/sec):         5.00              5.00
            Deflection to Jounce Stop (in):       -4.00             -4.00
                  Stop Linear Rate (lb/in):      300.00            300.00
                 Stop Cubic Rate (lb/in^3):      600.00            600.00
                Stop Energy Ratio (%/100):         0.50              0.50
           Deflection to Rebound Stop (in):        4.00              4.00
                  Stop Linear Rate (lb/in):      300.00            300.00
                 Stop Cubic Rate (lb/in^3):      600.00            600.00
                Stop Energy Ratio (%/100):         0.50              0.50
             Roll Steer Const. Coef (deg):         0.00              0.00
           Roll Steer Linear Coef (deg/in):        0.00              0.00
        Roll Steer Quadratic Coef (deg/in):        0.00              0.00
            Roll Steer Cubic Coef (deg/in):        0.00              0.00


                         Camber and Half-track Tables

       -------- Right Side -------        -------- Left Side --------
        Susp          1/2-track            Susp          1/2-track
        Defl   Camber   Change             Defl   Camber   Change
        (in)    (deg)    (in)              (in)    (deg)    (in)
       -4.00    0.50    0.00              -4.00    0.50    0.00
        0.00    0.50    0.00               0.00    0.50    0.00
        4.00    0.50    0.00               4.00    0.50    0.00

     Tire Information, Second Axle ---
                                              Right Side        Left Side
                                              ----------        ----------
                               Tire Name:       Generic           Generic
                       Tire Manufacturer:       Generic           Generic
                              Tire Model:       Generic           Generic
                               Tire Size:    P195/60R15        P195/60R15
                              Version No:      V  5.20           V  5.20
                     Unloaded Radius (in):       12.10             12.10
                Static Loaded Radius (in):       11.67             11.67
                     Nominal Width (in):          7.68              7.68
                       Tread Width (in):          6.14              6.14
      Init. Radial Stiffness (lb/in/tire):     1506.33           1506.33
        2nd Radial Stiffness (lb/in/tire):    15063.30          15063.30
```

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Vehicle Data-SIMON, Event                                HVE 2018 Version 14.00
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             Defl. @ 2nd Stiffness (in):             3.68             3.68
                    Max Deflection (in):             4.61             4.61
         Rebound Energy Ratio (%/100):               1.00             1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in/             7.90             7.90
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in             3.89             3.89
      Weight (Tire+Whl+Brk, lb/tire):               41.11            41.11
               Roll Resistance Const:                0.01             0.01
Roll Resististance Linear Coef (sec/in):             0.00             0.00
                Min Fz For Skidmark (lb):          308.00           308.00
                    Pneumatic Trail (in):           -0.86            -0.86

  Cornering Stiffness (lb/deg/tire):      Right Side             Left Side
                                    ----------------------------------------------
                        Loads (lb):   607.3  1230.1  1845.7   607.3  1230.1  1845.7
                   Speeds (in/sec):   528.0                   528.0
                          Load No.:       1       2       3       1       2       3
                      Speed No. 1:   226.9   226.9   226.9   226.9   226.9   226.9

     Camber Stiffness (lb/deg/tire):      Right Side             Left Side
                                    ----------------------------------------------
                        Loads (lb):   613.2  1235.7  1856.8   613.2  1235.7  1856.8
                   Speeds (in/sec):   528.0                   528.0
                          Load No.:       1       2       3       1       2       3
                      Speed No. 1:     5.0    12.5    19.2     5.0    12.5    19.2

                Tire Friction Table:      Right Side             Left Side
                                    ----------------------------------------------
                        Loads (lb):   616.0  1229.0  1842.0   616.0  1229.0  1842.0
                   Speeds (in/sec):   528.0                   528.0
            Speed No. 1, Load No.:       1       2       3       1       2       3
                           Peak Mu:  0.9810  0.9890  0.9940  0.9810  0.9890  0.9940
                          Slide Mu:  0.8660  0.7560  0.6750  0.8660  0.7560  0.6750
            Slip @ Peak Mu (%/100):  0.2440  0.1680  0.1460  0.2440  0.1680  0.1460
       Long. Stiffness (lb/slip): 10000.0 10000.0 10000.0 10000.0 10000.0 10000.0

     Brake Information, Second Axle ---
                                                 Right Side        Left Side
                                                 ----------        ----------
                     Brake Assembly Type:    Generic Brake     Generic Brake
                    Brake Time Lag (sec):           0.0000            0.0000
                   Brake Time Rise (sec):           0.0000            0.0000
                  Pushout Pressure (psi):             5.00              5.00
 Nominal Brake Torque Ratio (in-lb/psi):             18.05             18.05
     Brake Proportioning Pressure (psi):            200.00            200.00
              Brake Proportioning Ratio:              0.33              0.33
```

```
Untitled                                                  Fri 11/01/19 11:28:58
References-SIMON, Event                                  HVE 2018 Version 14.00
Licensed User: Engineering Systems, Inc.                                 PAGE 2
```

16. Deyerl, E.S., Fitch, M.J., 'Evaluation of the Automatic Transmission Model in HVE Version 7.1,' Dial Engineering, HVE White Paper No. WP-2003-1, Engineering Dynamics Corporation, Beaverton, OR, 2010.

Appendix E - PC-Crash Nominal Run Inputs

START VALUES	
Velocity [mph] :	42.12
Friction coefficient :	0.70
BRAKE	
maximum stopping distance [ft] :	300.00
Brake force [%]	
Axle 1, left :	8.34
Axle 1, right :	8.34
Axle 2, left :	500.00
Axle 2, right :	5.11
mean brake acceleration [g] :	-0.19
STEERING	
Steering time [s] :	5.00
New steering angle [deg]	
Axle 1 :	0.33
Axle 2 :	0.00
Turning circle [ft] :	3097.46

INPUT VALUES

Vehicle :	HONDA-ACCORD LX/SPORT/EX-L/TOURING 4DR S
Database:	DB_USDBASE
RecordID:	4
Length [in] :	184.80
Width [in] :	72.83
Height [in] :	57.87
Number of axles :	2
Wheelbase [in] :	107.04
Front overhang [in] :	37.80
Front track width [in] :	57.96
Rear track width [in] :	57.96
Mass (empty) [lb] :	3186.00
Total weight [lb] :	3186.00
Mass of front occupants [lb] :	0.00
Mass of rear occupants [lb] :	0.00
Mass of cargo in trunk [lb] :	0.00
Mass of roof cargo [lb] :	0.00
Distance C.G. - front axle [in] :	44.40
C.G. height above ground [in] :	21.12
Roll moment of inertia [lbfts^2] :	600.00
Pitch moment of inertia [lbfts^2] :	2000.00
Yaw moment of inertia [lbfts^2] :	2000.00
Stiffness, axle 1, left [lb/in] :	170.40
Stiffness, axle 1, right [lb/in] :	170.40
Stiffness, axle 2, left [lb/in] :	108.94
Stiffness, axle 2, right [lb/in] :	108.94
Damping, axle 1, left [lb-s/ft] :	230.03
Damping, axle 1, right [lb-s/ft] :	230.03
Damping, axle 2, left [lb-s/ft] :	147.07
Damping, axle 2, right [lb-s/ft] :	147.07
Max. slip angle,axle 1, left [deg]:	10.00
Max. slip angle,axle 1, right [deg]:	10.00
Max. slip angle,axle 2, left [deg]:	10.00
Max. slip angle,axle 2, right [deg]:	10.00
ABS :	No

Vehicle :	HONDA-ACCORD LX/SPORT/EX-L/TOURING 4DR S
Database:	DB_USDBASE
RecordID:	4

START VALUES

Velocity magnitude (v) [mph] :	**42.12**
Heading angle [deg] :	90.00
Velocity direction (ß) [deg] :	72.90
Yaw velocity [Deg/s] :	436.43
Center of gravity x [ft] :	0.00
Center of gravity y [ft] :	0.00
Center of gravity z [ft] :	1.76
Velocity vertical [mph] :	-0.00
Roll angle [deg] :	0.00
Pitch angle [deg] :	0.00
Roll velocity [Deg/s] :	0.00
Pitch velocity [Deg/s] :	0.00

END VALUES

Velocity magnitude (v) [mph] :	**0.23**
Heading angle [deg] :	28.02
Velocity direction (ß) [deg] :	-4.44
Yaw velocity [Deg/s] :	0.30
Center of gravity x [ft] :	27.86
Center of gravity y [ft] :	110.94
Center of gravity z [ft] :	1.76
Velocity vertical [mph] :	0.01
Roll angle [deg] :	-2.95
Pitch angle [deg] :	0.59
Roll velocity [Deg/s] :	7.40
Pitch velocity [Deg/s] :	-0.25

SEQUENCES

1 HONDA-ACC :

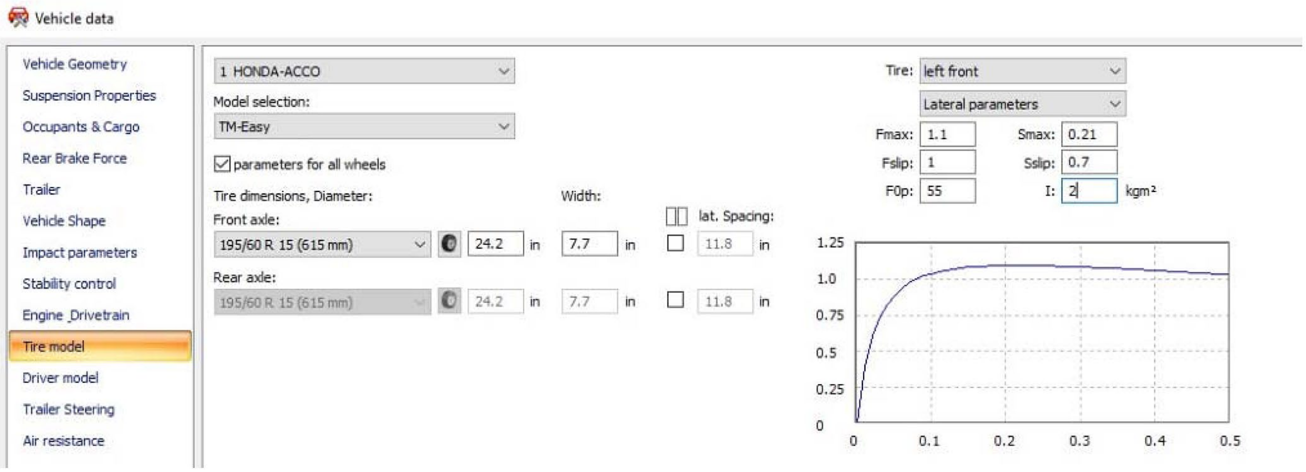
REACTION	
Reaction time [sec] :	1.00
BRAKE LAG	
Threshold time [sec] :	0.20
BRAKE	
maximum stopping distance [ft] :	32.81
Brake force [%]	
Axle 1, left :	0.00
Axle 1, right :	0.00
Axle 2, left :	0.00
Axle 2, right :	0.00
mean brake acceleration [g] :	0.00

SECTIONS

1 HONDA-ACC :

	Time [s],	Dist. [ft],	Vel. [mph]
	0.00	0.00	0.0
Reaction			
	0.00	0.00	0.0
Brake Lag			
	0.00	0.00	0.0
Brake			
	0.00	0.00	0.0
Start (t=0s)			
	0.00	0.31	42.1
Brake			
	3.62	114.74	0.2

user defined vehicle positions


Vehicle data
Vehicle Geometry
Suspension Properties
Occupants & Cargo
Rear Brake Force
Trailer
Vehicle Shape
Impact parameters
Stability control
Engine Drivetrain
Tire model
Driver model
Trailer Steering
Air resistance
1 HONDA-ACCO
Model selection:
TM-Easy
parameters for all wheels
Tire dimensions, Diameter:
Width:
lat. Spacing:
Front axle:
195/60 R 15 (615 mm)
24.2 in
7.7 in
11.8 in
Rear axle:
195/60 R 15 (615 mm)
24.2 in
7.7 in
11.8 in
Tire: left front
Lateral parameters
Fmax: 1.1
Smax: 0.21
Fslip: 1
Sslip: 0.7
F0p: 55
I: 2 kgm²
1.25
1.0
0.75
0.5
0.25
0
0
0.1
0.2
0.3
0.4
0.5

Appendix F - VCRware Nominal Run Inputs

vdynXL RUN 02 nominal.xlsm
10/26/2019
version 4.1

Vehicle Dynamical Simulation

	Single Vehicle (or Tow Vehicle)				Semitrailer	
	Weight, Wc, lb	yaw inertia, Jc, ft-lb-s^2			Weight, Wt, lb	Inertia, Jt, ft-lb-s^2
weight, yaw inertia	3186.00	2000.00			2000.00	2000.00
	L_1	L_2	L_3	L_4	L_5	L_6
lengths, ft	3.70	3.70	5.22	5.22	5.00	5.00
	W_1	W_2	W_3	W_4	W_5	W_6
widths, ft	2.42	2.42	2.42	2.42	3.00	3.00
			L_{CP}	W_{CP}	L_{TP}	W_{TP}
trailer/pin dimensions, ft			0.00	0.00	5.00	3.00
	h_C				h_T	
center of gravity heights, ft	1.76				4.00	
tire lateral (steering)	$C_{\alpha 1}$	$C_{\alpha 2}$	$C_{\alpha 3}$	$C_{\alpha 4}$	$C_{\alpha 5}$	$C_{\alpha 6}$
coefficients, lb/rad	13000.0	13000.0	13000.0	13000.0	13000.0	13000.0
Longitudinal BNP Constants	BNP-Cx	1.40	BNP-Ex	0.60	1.50	0.50
values $0 < C_x < 2.0$, $-5 < E_x < 1.2$	C_{s1}	C_{s2}	C_{s3}	C_{s4}	C_{s5}	C_{s6}
coefficients, lb	10000.0	10000.0	10000.0	10000.0	13000.0	13000.0
Lateral BNP Constants	BNP-Cy	1.50	BNP-Ey	0.50	1.40	1.00
values $0 < C_y < 2.0$, $-5 < E_y < 1.2$	s_1	s_2	s_3	s_4	s_5	s_6
wheel brake slip, values, $0 < s < 1$	0.0430	0.0430	1.0000	0.0168	0.000	0.000
wheel acceleration	T_1	T_2	veh accel, g's	0.00	T_5	T_6
traction coefficients, T (0 or 1)	0	0	0	0	0	0
aero drag coeffs, ft^2	$C_{DCX}A_{XC}$	$C_{DCY}A_{YC}$	W_X	W_Y	$C_{DTX}A_{XT}$	$C_{DTY}A_{YT}$
and wind speeds, W, ft/s	0.00	0.00	0.00	0.00	0.00	0.00
				L_C		L_T
front-to-rear aero force offset, ft				0.00		1.00
	Xc, ft	Xc - Vel, ft/s	Yc, ft	Yc - Vel, ft/s		
initial conditions	0.00	18.17	0.00	-59.04		
	θ_C, deg	θ_C - Vel, °/s			θ_T, deg	θ_T - Vel
initial conditions	-90.00	-436.43			0.00	0.00
Lane Change steer angle, deg	0.000					
g, ft/s^2	32.17					

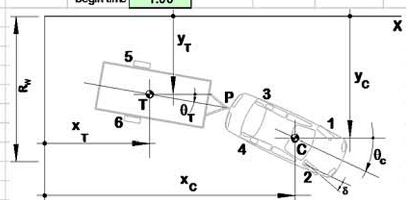
				friction coefficients	
	R_W, road			road	shoulder
roadway	width, ft			f_R	f_B
parameters	24.0			0.700	0.700
	integration	print	steering	number of	
program	interval, s	interval	mode, KM	wheels	
run	0.0050	10	-1	4	no trailer
parameters	final time, s			1	MEQ (0/1)
	5.00		KM	mode	
			-1	tabular steer (S5:T25)	
	lane change		0	all wheels locked	
	duration, s	4.00	1	lane change	
	begin time	1.00			

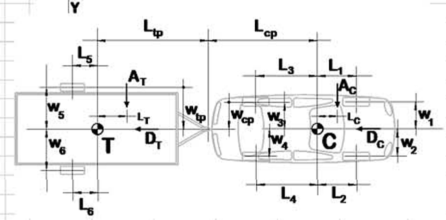
Run vdynXL

Unit Conversion

US

tabular front wheel steer angles, KM = -1	
time, s	δ, deg
0.000	0.00
0.500	0.00
1.000	0.00
1.500	0.00
2.000	0.00
2.500	0.00
3.000	0.00
3.500	0.00
4.000	0.00
4.500	0.00
5.000	0.00
5.500	0.00
6.000	0.00
6.500	0.00
7.000	0.00
7.500	0.00
8.000	0.00
8.500	0.00
9.000	0.00
9.500	0.00
10.000	0.00





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