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Software Integration for Simulation-Based Analysis and Robust Design Automation of HMMWV Rollover Behavior

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ABSTRACT

A multi-body dynamics model of the U.S. Army's High Mobility Multi-purpose Wheeled Vehicle (HMMWV) has been created using commercial software (ADAMS) to simulate and analyze the vehicle's rollover behavior. However, manual operation of such simulation and analysis for design purposes is prohibitively expensive and time consuming, limiting the engineers' ability to utilize the model fully and extract from it useful design information in a timely, cost-effective manner. To address this challenge, a commercial system integration and optimization software (OPTIMUS) is utilized in order to automate the simulation processes and to enable the more complex uncertainty-based analysis of the HMMWV rollover behavior under a variety of external conditions. Challenges involved in integrating the software are highlighted and remedies are discussed. Rollover analysis results from using the integrated model and automated simulation are also presented. The results offer important information and design insights that would have been very difficult to obtain without the automation provided by the integrated software.

INTRODUCTION

The HMMWV was not originally designed (c. early 1980's) to be an armored vehicle. However, recent operations have created a need for additional crew protection against ballistic and explosive threats. The Army's strategy for adding crew protection to the current HMMWV fleet is to add armor, substantially increasing the vehicles' weight. One negative consequence of this added weight is that it makes the vehicle more susceptible to rollover. It is clear that to mitigate this rollover hazard and maintain (or improve) the HMMWV's durability, it is necessary to rework the design of other vehicle components and subsystems. Fortunately, powerful new computer-based design optimization tools have been developed and may be brought to bear on this problem. These tools are used in a study intended to improve HMMWV rollover characteristics in the presence of uncertainty. Such a study will not only complement existing technical knowledge of the HMMWV, but also provide valuable insights to improve upon the present and future HMMWV designs.

Rollover study of the HMMWV in various missions and scenarios can be performed virtually using engineering models and simulations. However, manual operation of such simulations and analysis is prohibitively expensive and time consuming, limiting the engineers' ability to utilize the model fully and extract from it useful design information in a timely, cost-effective manner. Availability of mature commercial software for model integration and design automation provides a solution to this limitation. Integrating existing HMMWV model into such software allows for rapid and rigorous rollover simulations and analysis; a task not feasible when performed manually. However, there are some challenges that must be overcome before successful integration, and the subsequent rollover study, can be achieved.

This article presents a simulation-based rollover study of a HMMWV via integration of the ADAMS multi-body dynamics model into the design integration software OPTIMUS. The rest of article is organized as follows. The next section provides a brief description of the commercial software OPTIMUS. It is followed by a description of the test procedure used to assess rollover behavior, and then by a description of the ADAMS model. Details of the integration process and the

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challenges involved are presented afterwards. Rollover studies conducted using the integrated models are described next along with the results obtained. The article is concluded with a brief summary.

INTEGRATION SOFTWARE: OPTIMUS

OPTIMUS [1] is a general-purpose software for process integration and design optimization. With OPTIMUS a designer can capture any existing simulation process and then automate the computation for design space exploration, numerical optimization, and robustness and reliability improvement of the design. The process automation module of OPTIMUS captures and automates the simulation process. The design exploration module provides tools for parameter identifications and response surface modeling among others. The numerical optimization module contains algorithms for searching the best design among all alternatives. The robust design module accounts for variability and uncertainty in design.

OPTIMUS is capable of integrating any type of simulation software, either a single code (e.g., stress, crash, fluid flow) or sequences of multi-disciplinary software – including in-house developed codes. These technologies are supported through a user-friendly and powerful interface that lowers the user's learning curve. The process capturing is performed graphically where the process builder creates a simulation workflow on the screen and positions icons representing the different parts of his/her process. Inputs, outputs, vectors, analyses are colored icons linked through arrows representing the flow of information.

In addition to these basic features, OPTIMUS also offers a variety of advanced tools for a designer. OPTIMUS' unique deep-level parallelization capability allows users to easily interface the OPTIMUS host to a computer cluster, and to submit a large number of jobs in a transparent manner. Built-in drivers to commercially available simulation codes such as CATIA, ABAQUS, MATLAB, MS-Excel, and others are also available to facilitate the interfacing process. OPTIMUS also provides flexibility in incorporating user-defined algorithms for use in design of experiments, response surface modeling, or design optimization. These features make OPTIMUS a particularly powerful tool to automate the HMMWV rollover simulation for design purposes.

ROLLOVER TEST PROCEDURE

To study the HMMWV rollover behavior in a simulation-based environment, the J-turn test maneuver as defined by the National Highway Traffic Safety Administration (NHTSA) is used [2]. This test is adopted to evaluate the dynamic rollover propensity of the HMMWV (a single step-steer input). Description of the maneuver is as follows.

The J-turn maneuver used in this study is performed on a flat terrain. To begin the maneuver, the HMMWV is driven in a straight line at a predefined entrance speed v_0. The throttle is then released and the HMMWV is turned (right or left) by turning the steering wheel angle to a specified angle θ_0. The turning rate of the steering wheel is fixed at 1000 deg/sec. After the angle θ_0 is achieved, the steering wheel position is maintained for four seconds. Afterwards, the steering wheel angle is returned to the θ=0° position within two seconds to complete the maneuver. Figure 1 shows the time profile of the maneuver in terms of the steering wheel angle θ.

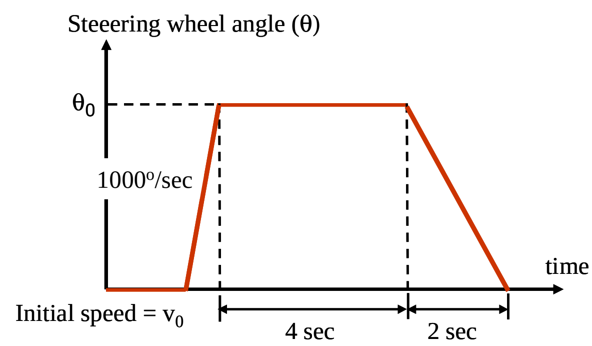

Figure 1. Time profile of NHTSA J-turn maneuver

During the J-turn maneuver, three rollover characteristics of the HMMWV are measured and monitored: roll rate, roll angle, and lateral acceleration. Since these values are dynamically changing over the time period of the maneuver, their maximum values are used in determining occurrence of rollover. The HMMWV is considered to be experiencing rollover when the maximum value of any of the three characteristics exceeds a predetermined threshold.

HMMWV MODEL

The multi-body dynamics model of the HMMWV in ADAMS [3] is shown in Fig.2. The vehicle model consists of the road model, the tire model, the suspension model, and the chassis model. Models for the tie-rods, steer link, and other components of the HMMWV are part of the assembled model. The HMMWV body structure model and the engine model are not shown.

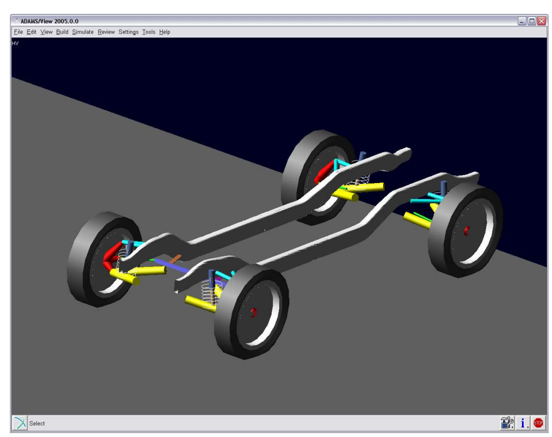

Figure 2. Multi-body dynamics model of the HMMWV

The road model is a finite element model that profiles the terrain, which in this particular study is a flat road. The tires are modeled following ADAMS' `UATIRE` tire property format by defining the tire dimensions, vertical stiffness and damping, rolling resistance, slip coefficients, and other tire parameters. The double-wishbone suspension is modeled as a rigid body system with fixed geometric placement relative to the tires and the chassis. Spring stiffness, damping coefficients, and other properties of both the front and rear suspensions are defined according to the HMMWV specifications. The chassis model is also defined as a rigid body with pre-specified placement with respect to the suspensions.

ADAMS stores all specifications of the HMMWV model in the file `Flat_JT.adm`, where `Flat_JT` is the user-defined name of the model. Conventionally, an engineer wanting to perform a simulation using the model must manually defines parameters of the simulation (steering wheel angle, time steps, etc.), and then activates the "Start Simulation" button, which is also a manual operation. ADAMS will then use the model defined in the `Flat_JT.adm` file to perform the requested operation, and return the simulation results in the file `Flat_JT.out`. Results of the simulation can be analyzed either by invoking the "Part Measurement Display" feature in ADAMS/View, or by exporting them to ADAMS/Insight. Both options require user interactions and manual operations of the software. Clearly, such user-dependent ADAMS simulation run prohibits an extensive study of the HMMWV rollover behavior.

MODEL INTEGRATION

To automate the rollover study, the HMMWV model is integrated into OPTIMUS. The first step in the integration is to define a process flow of the HMMWV rollover simulation in OPTIMUS: the inputs, the models, and the outputs.

Four components of the HMMWV and two parameters of the J-turn maneuver are taken to be inputs in this study. The four HMMWV components are the stabilizer bar, the body-mount bushing, and the front and rear suspensions. The two J-turn parameters are the entrance speed v_0 and the maximum steering wheel angle θ_0. The speed v_0 and the wheel angle θ_0 are defined as the first and second design variables, respectively. Nineteen additional design variables are defined based on the four HMMWV components, for a total of 21 design variables in this rollover study.

Of the 19 HMMWV component design variables, one is defined to quantify the torsional stiffness of the stabilizer bar; three to quantify the bushing stiffness with respect to the x, y, and z-axis; and 15 variables are defined to quantify the damping characteristics of the front and rear suspensions. Damping characteristics of the suspensions are defined by a 3rd degree polynomial in the force vs. velocity space. Seven of the 15 damping variables are used to define the values in the velocity axis (same values for both front and rear suspensions). The other eight variables are used to define the coefficients of the polynomial: four each for the front and rear suspensions. Figure 3 shows the input variable definition window in OPTIMUS.

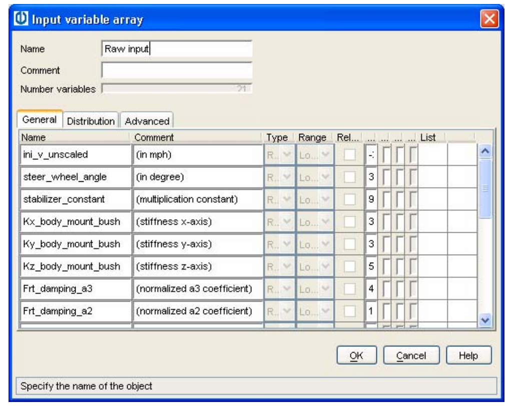

Figure 3. Input variable definition in OPTIMUS

These inputs are then fed to the model block in OPTIMUS. This block loads and runs the J-turn simulations in ADAMS automatically by invoking the `mdi.bat` file, a top level batch command file provided by MSC Software. The `mdi.bat` command takes two inputs: a `ST.dll` file and a `Flat_JT.acf` file. The `ST.dll` file is an ADAMS dynamic library file provided by MSC Software. The `Flat_JT.acf` file is a user-defined file containing ADAMS input-output file declaration and the simulation command. Since the J-turn maneuver consists of two driving profiles, straight line and right/left turn, we need to invoke `mdi.bat` twice. For this purpose, we created a shell batch file `runADAMS.bat` for use as an executable in OPTIMUS. The commands in `runADAMS.bat` are as follows:

```
call mdi ru-u ST.dll Flat_JT_1.acf
call mdi ru-u ST.dll Flat_JT_2.acf
```

where the first command runs the straight line driving maneuver as defined in `Flat_JT_1.acf`, and the second command runs the turning maneuver as defined in `Flat_JT_2.acf`.

The `Flat_JT_1.acf` file contains the following commands:

```
Flat_JT.adm
Flat_JT.out
SIMULATE/DYNAMIC, END=6.0, DTOUT=1.0E-002
SAVE/SYSTEM, FILE=INI.SAV
STOP
```

The first two lines of the file define ADAMS input and output files, respectively, and the next three lines instruct ADAMS to perform the straight line maneuver for six seconds. The `Flat_JT_2.acf` file contains the following commands:

```
Flat_JT.adm
Flat_JT.out
REL/SYSTEM, FILE=INI.SAV
```

```
DEA/SFORCE, ID=10,11,12,13
MOTION/1, ROT, JOINT=10,
FUNCTION=STEP(TIME,7,0,7.33,0.1211)
SIMULATE/DYNAMIC, END=12.0, DTOUT=0.01
STOP
```

Similar to before, the first two lines are the input-output file declaration. The command in the third line instructs ADAMS to load and continue the simulation performed by `Flat_JT_1.acf`. The rest of the commands define the input forces and time profile corresponding to the turning maneuver in the J-turn test.

Outputs from the J-turn simulation are saved in the `Flat_JT.out` file. Three of these outputs are of particular interest in this study and are used to determine occurrence of rollover: roll rate, roll angle, and lateral acceleration. To create a database for future study, 16 other outputs of the simulation are also recorded. They are: steering wheel angle; longitudinal velocity, lateral velocity, and vertical displacement of the vehicle CG; CG pitch rate and angle; CG yaw rate and angle; normal forces on the four tires; and vertical displacement of the tire centers. OPTIMUS reads and records these outputs by parsing the `Flat_JT.out` file. Since the simulation is dynamic, vectors of time-history of each output are recorded. Maximum values of these vectors are also calculated for use in the study. Figure 4 shows the output definition window in OPTIMUS.

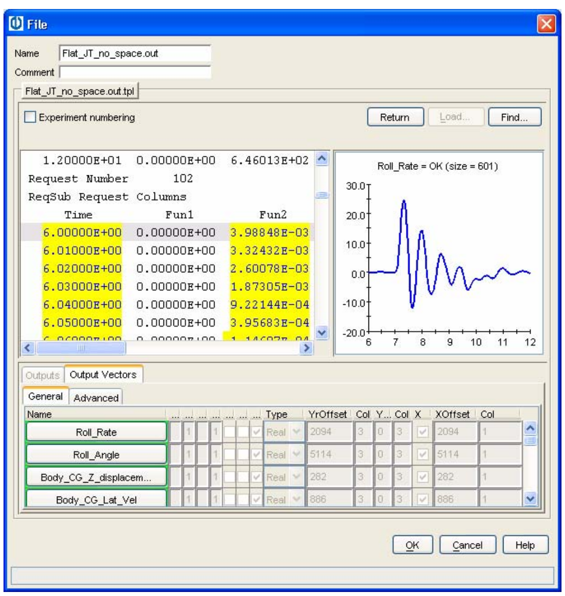

Figure 4. Output definition in OPTIMUS

INTEGRATION CHALLENGES

After the inputs, models, and outputs are fully defined, we need to link them together to create a complete process flow in OPTIMUS. Conventionally, this link is straightforward: input to model to output. However, in this particular study, a couple of challenges must be addressed before the three OPTIMUS components can be linked together.

The first challenge is in linking the input variables to the ADAMS model. Two obstacles prohibit direct linking of these two components: unit mismatch and differing damping characteristics quantification. To facilitate NHTSA J-turn test specifications, the speed variable v_0 and the steering angle variable θ_0 are defined in miles per hour and degree angle, respectively. However, the ADAMS model uses as standards the units: radians, mm, kg, and seconds in its definition. As such, the two variables cannot be directly used in the model. This unit mismatch also exists in the other input variables; for instance, we define the bushing stiffness in N/m instead of N/mm. In addition to unit mismatch, input variables for the suspension damping also cannot be directly used because ADAMS requires a vector of paired force-velocity values as inputs, while we use coefficients of the polynomial as input variables. To overcome these obstacles, we create a vector of temporary input variables that converts the original input variables into the proper format used by ADAMS. Both the original and temporary input variables are then linked to the `Flat_JT.adm` and the `Flat_JT_2.acf` files.

The second challenge is in parsing the output file `Flat_JT.out`. During the simulation run, ADAMS records the requested output values as columns of time-histories, with the first column containing the time values. Following its built-in format, ADAMS inserts an empty line after every five lines in these columns of values. However, this creates a problem for OPTIMUS in reading the values because for OPTIMUS an empty line is a termination token. These empty lines cause OPTIMUS to read only the first five lines of the values, regardless of how many values exist in the entire time history. To evade this problem, we create a shell command to remove the empty lines in the `Flat_JT.out` file before OPTIMUS output parsing. The command is as follows:

```
grep "^ " $Flat_JT.out$ >
$Flat_JT_no_space.out$
```

Here `grep` is the shell command, the first argument `"^ "` indicates we are searching for empty lines, and the last two arguments define the names of the original and the transformed files.

With these two challenges addressed, OPTIMUS can then properly link all three components, inputs, models, and outputs together. Figure 5 shows the complete process flow of the HMMWV rollover simulation in OPTIMUS.

ROLLOVER STUDY

Using the integrated ADAMS model in OPTIMUS, two types of rollover studies are performed: deterministic and uncertainty-based. In the deterministic analysis, all parameters and settings of the simulation are assumed exact. The purpose of the deterministic study is to investigate the effect of different stabilizer bars on the HMMWV rollover behavior. The uncertainty-based analysis accounts for the uncontrollable variations that exist in reality [4, 5]. It is performed to study the robustness of the HMMWV design under the influence of uncertainty.

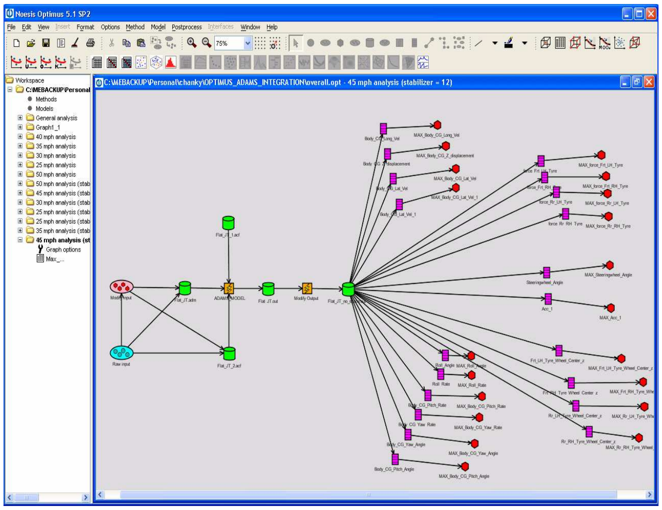

Figure 5. HMMWV rollover simulation process flow

DETERMINISTIC STUDY

For the deterministic study, we are interested in calculating the maximum angle, θ_0^{max}, that the HMMWV's steering wheel can be turned in the J-turn maneuver before the vehicle experiences rollover. The angle is calculated as a function of the entrance speed v_0. Eight v_0 values are specified in this study, and they represent the HMMWV's typical operational speed. For each v_0 value, multiple rollover simulations are run in OPTIMUS. In these runs, OPTIMUS automatically increases the steering wheel angle θ_0, starting from a low value, until rollover is observed. The wheel angle value before rollover occurrence is taken to be the θ_0^{max} for that particular v_0.

To also investigate the effect of a stabilizer bar on the v_0- θ_0^{max} characteristics of the HMMWV, three stiffness values of the bar are specified. The v_0- θ_0^{max} runs as described above are then conducted for each of these values. Values for other input variables are held constant following the vehicle specification. Figure 6 shows the v_0- θ_0^{max} curves of the HMMWV for the three stabilizer bar types. In this figure, the region below the curves indicates those combinations of v_0- θ_0 values for which there is no rollover. In contrast, rollovers are observed in the region above the curves.

There are several important observations that can be made from Fig.6. First, we observe that θ_0^{max} decreases as v_0 increases. This behavior is expected because higher entrance speed in the J-turn maneuver makes the vehicle more prone to rollover. In addition, we also observe that for low values of v_0, θ_0^{max} becomes saturated. This saturation value is the maximum angle the HMMWV steering wheel can be turned. This implies that for this low speed range, the HMMWV will never rollover when performing a J-turn. The shape of the v_0- θ_0^{max} curves for different stabilizer bars is similar. However, there is a particular value of v_0 for which the HMMWV behavior differs. This v_0 value corresponds to the natural frequency of the vehicle, and as such it is more sensitive to changes in its components properties. No change in the v_0- θ_0^{max} curve is observed for other v_0 values.

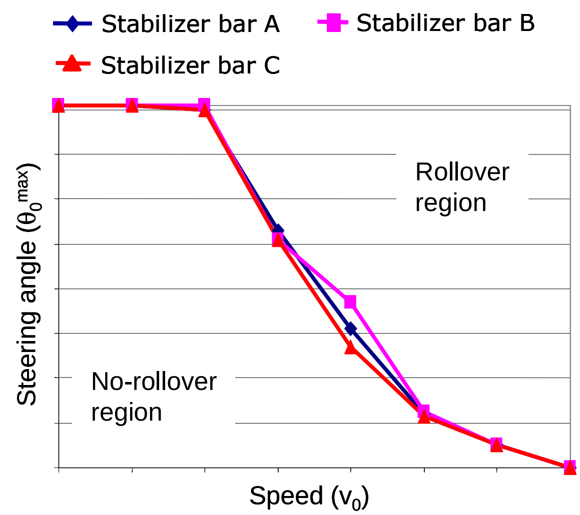

Figure 6. The v_0- θ_0^{max} curves of the HMMWV

UNCERTAINTY-BASED STUDY

In the uncertainty-based study, we want to investigate the impact of variations in the vehicle mass and CG location on its rollover behavior. Variations in mass and CG of the vehicle are assumed to occur due to random addition of three HMMWV operational components: human personnel, cargo load, and additional armor. All three components are modeled as lump masses with appropriate values for their masses and CG locations specified. It is further assumed that the random addition of the three components follows the discrete probability distribution shown in Fig.7. As seen in Fig.7, there are eight cases of possible combination of additional masses. The cases range from the vehicle having only one personnel inside it (the driver), to having both a driver and a passenger in addition to hauling a cargo with additional armor.

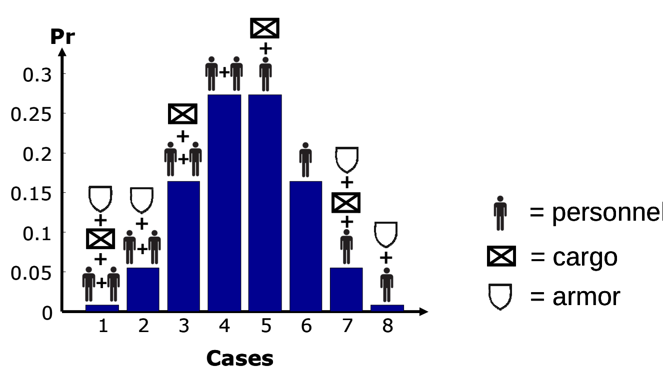

Figure 7. Assumed distribution of additional mass

Similar to the deterministic study, here we are also interested in determining θ_0^{max} as a function of v_0.

However, because we have a (discrete) distribution of vehicle mass and CG for each v_0 value, the analysis also results in a distribution of θ_0^{max} for each value of v_0, instead of just a single θ_0^{max} value. As such, unlike in the deterministic study, we need a different criterion in determining the critical steering angle value for a given v_0. From the previous deterministic study, it is observed that θ_0^{max} is a monotonic function of v_0. This implies that if the vehicle does not roll over when the steering wheel is turned to angle $\theta_{0,A}^{max}$, it will not roll over either when the angle is $\theta_{0,B}^{max} < \theta_{0,A}^{max}$. Using this monotonic property, we can then probabilistically define the critical steering angle θ_0^{max} to be the angle such that given v_0, the HMMWV will not rollover 95% of the time.

Based on this probabilistic criterion, we calculated the v_0- θ_0^{max} curve of the HMMWV under uncertain condition as shown in Fig.8. For comparison, the deterministic v_0- θ_0^{max} curve is also shown. As before, the vehicle experiences rollover for v_0- θ_0^{max} region above the curves, and there is no rollover for region below the curves. Stabilizer bar type A is used in this uncertainty-based study.

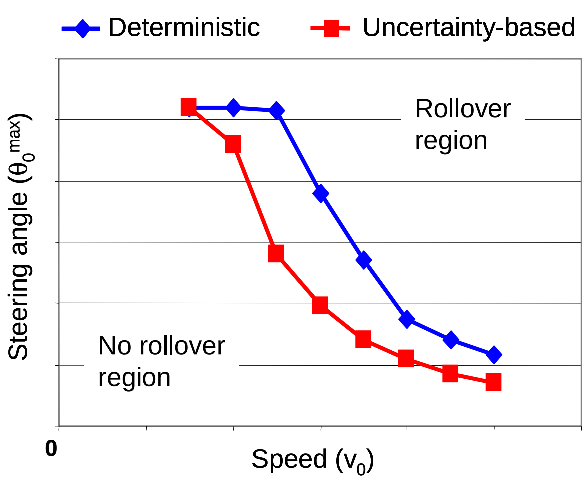

Figure 8. The deterministic and uncertainty-based v_0- θ_0^{max} curves of the HMMWV

We observe in Fig.8 that the v_0- θ_0^{max} curve of the vehicle with uncertainty consideration is considerably lower than that without. For low and high values of v_0, the difference in θ_0^{max} of the deterministic and uncertainty-based curves is relatively small, though still significant. For v_0 values near the natural frequency of the vehicle, however, the difference is substantial (as much as 50% reduction in θ_0^{max}). This observation implies that the vehicle is more susceptible to rollover when there is variation in its mass and CG location.

SUMMARY

A HMMWV ADAMS model has been integrated with the commercial software OPTIMUS for use in a rollover study. A top level batch command is utilized in the integration for automatic execution of the ADAMS simulation in OPTIMUS environment. There are two notable obstacles in the integration effort: (1) inability to directly link input variables of the rollover analysis to the ADAMS model, and (2) false parsing of ADAMS outputs by OPTIMUS due to different file-formatting standard. Intermediate variables are created to address the first obstacle. These variables transform the raw input variables into their respective counterparts in ADAMS. A shell batch command is used to solve the second obstacle. It reformats the ADAMS output file so that it is compatible with OPTIMUS file parsing procedure.

Using the automated simulation, two rollover studies are conducted: deterministic and uncertainty-based. In the deterministic study, all settings of the simulation are assumed exact. Results of this study show that there is a certain range of speed for which changes in the stabilizer bar influence the HMMWV rollover behavior. This speed corresponds to the natural frequency of the vehicle. In the uncertainty-based study, mass and CG location of the vehicle are assumed to be random due to addition of three mass components: personnel, cargo, and armor. Results of this study suggest that variations in the vehicle mass and CG have a significant impact on the rollover behavior. Therefore, when refitting existing HMMWV with additional armor or in designing future HMMWV systems, the issue of uncertainty must be accounted for.

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