SIMON Simulation of Non-Automotive Vehicle Free Rolling Response

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Abstract

Although the HVE SIMON physics module provides the ability to perform sophisticated simulations of crashes involving automobiles and trucks, it can also be used with other types of four wheeled vehicles. This paper describes the methodology used to study the free rolling response of a large commercial lawn mower after the unit lost power and rolled down a steep slope. The mower ultimately overturned, fatally injuring the operator. The unique challenges associated with modeling this type of machine are discussed, and avoidance scenarios studied are described. Specialized testing was used to provide appropriate values for some of the vehicle and site parameters needed for the HVE simulation.

Introduction

The event being studied occurred when the operator reportedly drove the mower up a slope at the municipal park where he was mowing. The mower's engine apparently stopped and the mower rolled backward down the slope until it overturned. The operator either jumped off of the machine or was ejected as it overturned, and was trapped under the mower deck when the mower tipped toward the left. A simulation was undertaken to study the unpowered dynamics of the mower, to determine how much time elapsed as the mower was rolling, and to evaluate whether the operator should have been able to stop before reaching the ditch.

The type of mower involved in this incident was a front drive, rear steer commercial model with three hydraulically actuated bat wing mowing decks, which were raised in the transport configuration (Figure 1). The mower's front wheels are driven by hydraulic motors which would normally be expected to present significant resistance to rolling, but testing of an exemplar mower revealed that the hydraulically selectable two speed front hubs could over-run when the hydraulic system was unpowered, allowing the machine to roll downhill with reduced resistance. The mower is also equipped with hydraulic service brakes, a mechanically actuated parking brake, and split steering brakes, all of which were functional at the time of the incident.

Figure 1. Mower decks raised for transport.

The site of the incident was a slope at a municipal park, shown in Figure 2. Investigating officers found tracks in the unmowed grass, leading from a position just right of the gravel path near the top of the slope to the lip of a ditch, near the center of the photograph. The investigators found no evidence of sliding along these tracks, and concluded that the operator did not attempt to stop the mower with the service brakes. They mapped these tracks, providing a reliable mower path for the simulation. The highest position for the mower was confirmed by witnesses on the far side of the slope, who stated that they saw the mower near the top and heard the engine stop.

Figure 2. Slope where incident occurred.

In order to create the terrain for the HVE environment model, the slope was mapped on a fine grid. This grid was then used to create a smooth surface in a 3D CAD system which was imported into HVE. These measurements also revealed that the peak slope along the tracks (approximately 17 degrees) exceeded the mower manufacturer's maximum recommended safe slope angle of 10 degrees. Mower geometry was created using a 3D laser scan of an exemplar mower. The exemplar mower was also used to make static and dynamic measurements needed in creating the HVE simulation.

Mower Static Testing

Static measurements of the exemplar mower included mass, center of gravity location, and tire rolling radius. Tire rolling radius was determined by measuring distance traveled on a level concrete surface for several wheel revolutions at each location. Tire pressure for these measurements was set according to the mower manufacturer's specifications. Center of gravity location was determined using scales and lifting one end of the mower with an overhead hoist (Figure 3). Tire compliance was also measured at each location using wheel scales and measured vertical displacement of the steel wheel at several wheel loads. The static stability ratio calculated using these measurements agreed well with tilt table testing of the mower according to the safety standard ANSI/OPEI B71.4-1999 [1].

Figure 3. Center of Gravity Measurement.

Mower Dynamic Testing

The construction of an HVE simulation which could faithfully mimic the free rolling response of the mower required precise measurement of the effective drag factor created by over-running of the two hydraulic drive motors. Measurements of the braking capacity of the service and steering brakes were also required. In order to make these measurements in a realistic setting, a test slope was used (Figure 4). The test slope was mapped in detail so that the slope angle could be measured and an HVE environment model created to duplicate the test conditions. The sloped section of the test site was approximately 35 feet long, and ended in an approximately level area long enough to safely bring the mower to a stop (Figure 5). The average slope angle for the test site was 13.8 degrees, which was comparable to the average slope angle at the incident site.

Figure 4. Test slope for determining drag factor.

Figure 5. Level area at bottom of test slope.

Test instrumentation consisted of a GPS-based VBOX mini, capable of measuring position, velocity, and acceleration. The test procedure used was to position the mower at the top of the slope, apply the service brakes, and stop the engine. The brakes were released, and the mower was allowed to roll rearward until it transitioned onto the level area. Service brakes were then used to stop the mower as quickly as possible. In most cases, the operator was able to lock the drive wheels with the service brakes. The velocity change over the first 30 feet of roll was used to calculate an effective drag factor, corrected for slope. Fourteen runs were used to calculate an average drag factor of 0.11 for the over-running condition. The velocity data was also used to calculate an effective braking drag factor as the mower came to a stop, which averaged 0.32 for the service brakes and 0.24 if the auxiliary steering brakes were used instead. Separate braking testing was also done on level concrete, yielding higher braking drag factors, but the lower values from the slope testing were used to obtain conservative estimates from the simulation results.

Simulation

The first step in the simulation activity was to determine the effective braking required to duplicate the performance measured in the slope testing. The HVE environment model of the test site was used for this purpose. A vehicle model for the mower was constructed from the generic automobile default, and using geometry based on 3D laser scans and created using Rhinoceros CAD software. The ability of HVE to define rear steering geometry enabled this characteristic to be accurately modeled. Custom tire models were created from measured geometry and the measured tire compressive stiffness. Other tire properties were scaled from the generic automotive tire default based on tire size. Suspension stiffness was set very high to better model the lack of suspension in the actual mower. A limiting factor on the maximum stiffness and damping that could be used was that using too high a value resulted in "hop" of the mower during a simulation event. This behavior is likely due to numerical problems with very stiff models and the fact that no tire hysteresis effect is available in the HVE tire model to absorb energy from bouncing.

The test slope model was then used to iterate on the amount of braking applied to match the effect of the measured drag factor at 30 feet of roll. Separate runs were used to determine the effective braking required to match the stopping performance measured in the testing. Because the effective braking was determined in this manner, no attempt was made to accurately model the geometry of the braking system of the mower.

Once the effective drag of the mower drive system had been determined, a simulation of the event could be run. The path of the mower during the incident was marked on the HVE environment, and a series of runs was done to determine any steering required to follow the path. Although the path follower option was tried, manual iteration of the steering history was ultimately used to achieve the best possible match. The approximate path distance from the top of the incident slope to the edge of the ditch was approximately 122 feet. The resulting simulation of the actual event calculated that the mower took approximately 8.6 seconds to reach the edge of the ditch after it started rolling rearward, reaching a top speed of approximately 12 mph. It was also found that, without steering input, the mower tended to move in a "hook" motion due to the side slope, deviating from the actual path observed. If the mower had moved in this fashion, it would likely have come to a stop after turning approximately 180 degrees, and might have headed forward down the slope.

Additional runs were done to study the potential ability of the operator to stop the mower before reaching the ditch. It was determined that, using the service brakes in a manner similar to the slope testing, the operator had approximately 7 seconds to perceive and respond by braking to stop the mower before reaching the ditch. Using the less powerful steering brakes, this time was reduced slightly, to 6.5 seconds.

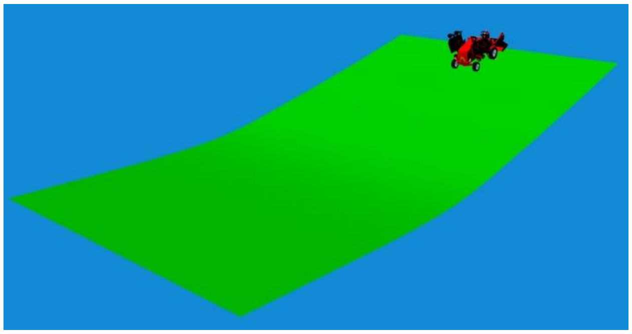

Figure 6. Test slope SIMON model.

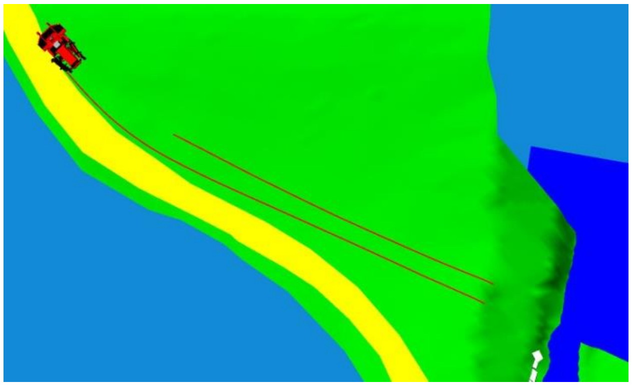

Figure 7. Incident site model showing path.

Figure 8. Deviation from path without steering.

Summary

The simulation effort described was used to gauge the likelihood that the operator was unable to stop the mower due to inadequate braking capacity of the mower. The simulation results clearly showed that this was not the case. In addition, the steering input required to follow the measured path strongly indicates that he was at least partially able to control the mower during its movement. No adequate explanation for the operator's lack of braking response was ever found.

References:

1. ANSI/OPEI B71.4-1999, *American National Standard for Commercial Turf Care equipment - Safety Specifications*, American National Standards Institute, 1999.

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