Simulation of Cannon Recoil Dynamics for Light Vehicles Using Single Body Models

David C. Rutledge, Ph.D.
Staff Engineer
United Defense
4800 East River Road
Minneapolis, MN 55421-1498

David.Rutledge@UDLP.com

SIMULATION OF CANNON RECOIL DYNAMICS FOR LIGHT VEHICLES USING SINGLE BODY MODELS

Firing a large caliber cannon mounted on a lightweight vehicle can result in severe pitching reaction angles and driver accelerations. These dynamic responses must be small enough to allow the crew and vehicle to fight effectively, hence their prediction is a key aspect of weapon integration with land vehicles. United Defense uses two classes of models to predict cannon firing dynamics:

- *Single body, time invariant, models that focus more on delivering timely results. These are best used to close in on the correct answer, which is appropriate for rapid prototyping efforts and trend studies.*
- *Multibody transient dynamic models such as Dynamic Analysis and Design System (DADS), which can deliver more accurate results. Such models are used for detailed design and development.*

The single body, time invariant, vehicle/suspension models developed at United Defense contain simplified representations of vehicle components, resulting in reduced modeling fidelity. The primary simulation inputs include firing impulse and peak force. The vehicle mass properties, geometry, and position of any stabilizers then determine vehicle response. The primary outputs are vehicle reaction angle and driver acceleration, which are determined by calculating the initial angular velocity, pitching and rolling moments, and lateral force from firing. The outputs are typically plotted as a function of cannon azimuth and elevation. The models are then tuned to correlate with previous results from firing data and DADS simulations, increasing their accuracy.

The presentation will go through the basic process of developing and using the models as described above. Plots will be presented showing typical reaction angles and driver accelerations for 18-ton class vehicles armed with a 120-mm class direct fire cannon and a 120-mm class mortar. A discussion of plots and their implications will finish the presentation.

1.0 INTRODUCTION

1.1 Motivation for Modeling Firing Dynamics

There currently exists a strong motivation for modeling the firing dynamics of cannon-armed vehicles. Force transformation will require powerful cannons to be mounted on relatively light armored vehicles. Firing such

Paper presented at the RTO AVT Symposium on "Functional and Mechanical Integration of Weapons and Land and Air Vehicles", held in Williamsburg, VA, USA, 7-9 June 2004, and published in RTO-MP-AVT-108.

a cannon causes a large vehicle dynamic response; the firing impulse causes a large upward angular reaction angle (the resultant of the pitch and roll angles) by the vehicle, while the firing peak force imparts a large acceleration on the vehicle driver. These angular reactions and driver accelerations must be small enough for the vehicle and crew to survive and fight effectively. Modeling is an important tool in designing towards this goal, because it facilitates the rapid prototyping process that leads to a test vehicle.

1.2 Types of Dynamic Models for Firing Dynamics

Two major categories of models are used to predict vehicle stability: detailed DADS models (Ref. 1) and single body models. DADS models include a higher level of geometric detail, component compliances, and component damping. These models focus on creating detailed time based simulations. Single body models include lower levels of geometric detail and no compliances/damping, resulting in reduced modeling fidelity. These models focus on creating rapid analyses and trend studies. This paper focuses on single body models as employed at United Defense for rapid concept development.

2.0 DESCRIPTION OF MODEL

2.1 Description of Single Body Model

The United Defense single body model is spreadsheet based. It is designed to be as flexible as possible, allowing calculations for either indirect or direct fire cannons, limited or full traverse, vehicles with or without spades, and wheeled or tracked suspensions. Figures 1 and 2 show a notional 18-ton tracked vehicle concept mounting a 120-mm cannon with full traverse and recoil spades at each corner. Figure 1 is a free body diagram showing the location of the following variables: peak force F; firing impulse I, vehicle weight M*g; horizontal ground reaction force Rx; and vertical ground reaction force Ry.

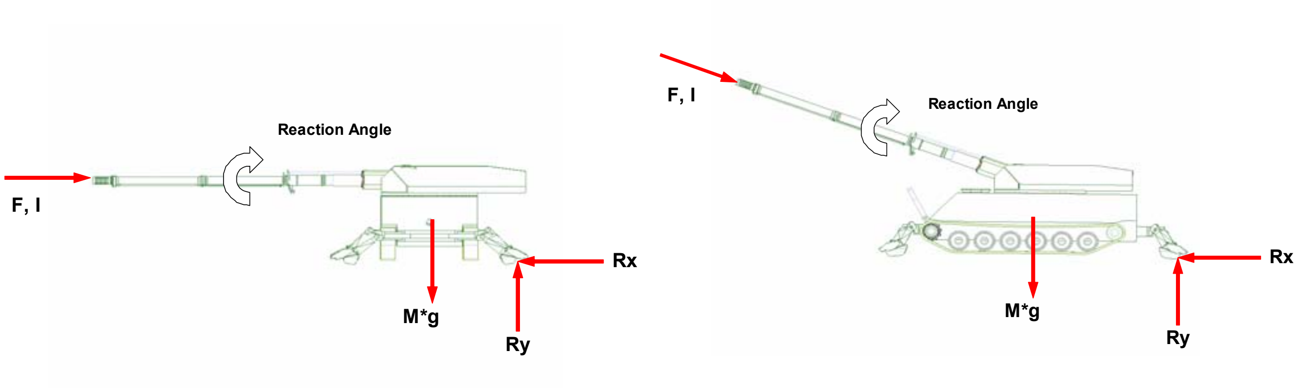

Figure 1: Notional Free Body Diagram

Figure 2 is a geometric diagram with the distance variable names defined with a capital letter followed by one or two small letters. The capital letters have the following meaning: longitudinal distance – L; height – H, and width – W. The small letters refer to the vehicle location being described: center of gravity – cg; driver – d; vehicle upper hull surface – v; cannon/gun – c, and spades - s. For example, Hc is the height of the cannon. The elevation of the gun is Elev.

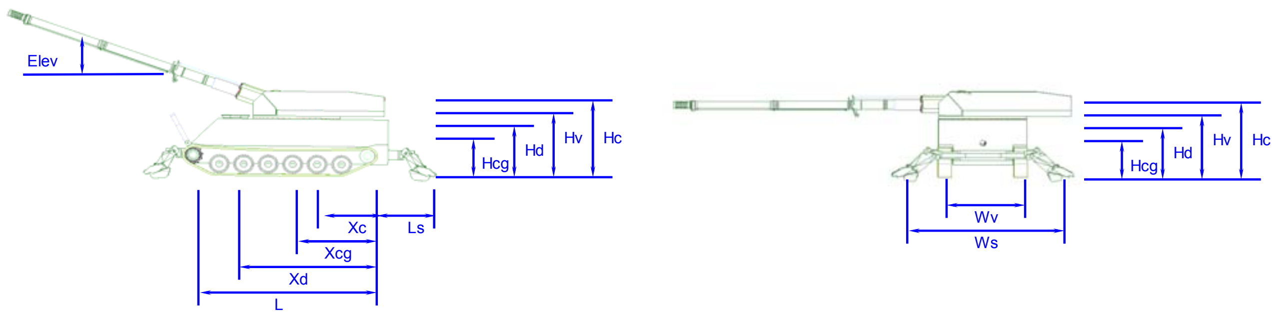

Figure 2: Notional Vehicle Geometric Variables

3.0 METHOD OF CALCULATION

3.1 Single Body Model Method of Calculation

The cannon firing impulse and peak force are the primary inputs for calculating the firing response. The cannon elevation, cannon traverse, and vehicle side slope are secondary but nevertheless major inputs. The vehicle mass/inertial properties, overall geometry, ground footprint, and spade locations then determine the vehicle dynamic response. When the vehicle does not use spades, the ground reaction is assumed to be where the wheels/tracks contact the ground; this simplification neglects the effect of suspension deflection on vehicle response. The model assumes no elastic deformation occurs to simplify the calculation of results. Based on these assumptions and inputs, the dynamic equations of motion are then generated for the vehicle concepts (Ref. 2).

The single body model contains fitting factors to compensate for the model's lower level of detail. The fitting factors represent those dynamic effects of the vehicle sinkage and slippage that have not been directly modelled. The factors are tuned to correlate the model output with the results from test firing data and DADS models. This process will be discussed in detail in section 4.0 of this paper.

3.2 Calculation of Maximum Vehicle Reaction Angle

The approach taken is to assume that all of the impulse from cannon firing is converted to kinetic energy of the vehicle (Ref. 3). This is a reasonable assumption as the cannon firing event is of very short duration compared to that of the vehicle's dynamic reaction. This allows calculation of the initial upward angular velocity of the vehicle. Assuming conservation of mechanical energy (no dissipative losses), this kinetic energy is converted completely to potential energy, resulting in the height that the Center of Gravity (CG) of the vehicle increases. The reaction angle that would raise the CG to that height is then calculated – this is the maximum reaction angle.

3.3 Calculation of Maximum Driver Acceleration

The approach taken is to use the cannon peak force to calculate the rolling moment and horizontal force on the vehicle at the instant the vehicle starts rotation (before it has moved). These values are used to calculate the angular and linear acceleration at the driver station, followed by the resultant acceleration - this is the maximum driver acceleration. This acceleration varies depending upon the driver location in the vehicle.

3.4 Analysis of Response for Typical Concepts

A simulation of the firing response at 0-degree traverse will illustrate a sample output from the one-body model. This will be an analysis of firing response as a function of firing impulse and elevation. This simulation is of a nominal concept with a 120-mm cannon with a recoil stroke is 20 inches. This armament is mounted on an 8x8 wheeled vehicle with a combat weight of 18 tons. Plots of the maximum pitch angle (same as reaction angle for 0-degree traverse case) versus cannon firing impulse and peak driver acceleration versus cannon peak force are shown in Figure 3. As shown, the cannon firing impulse is a key design variable for reducing vehicle reaction angle. Likewise, the peak firing force is a key design variable for reducing driver acceleration.

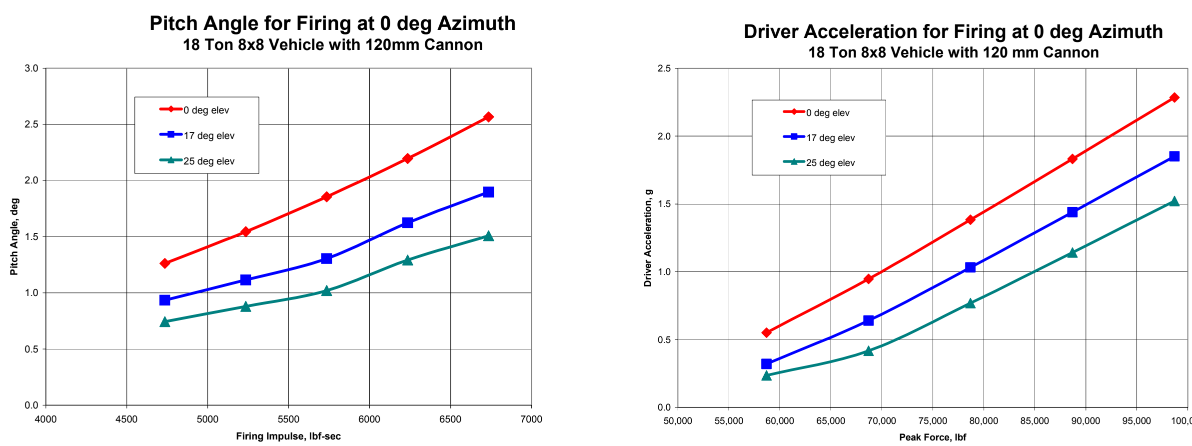

Figure 3: Notional 18-Ton Vehicle Response Versus 120-mm Cannon Inputs

A simulation of a much lighter 6x6 wheeled vehicle with a 120-mm mortar demonstrates the versatility of the single-body approach. This concept has ±30-degree traverse for the mortar, a firing impulse of 1,200 lbf-sec, a recoil stroke of 11 inches, and combat weight is 3 tons. Plots of the reaction angle and peak driver acceleration versus mortar traverse angle are shown in Figure 4. This concept is far different than the previous concept and its results are plotted against different independent parameters. Also plotted are results from a DADS simulation; these were used to derive the fitting factors needed to tune the model, as explained in section 4.0.

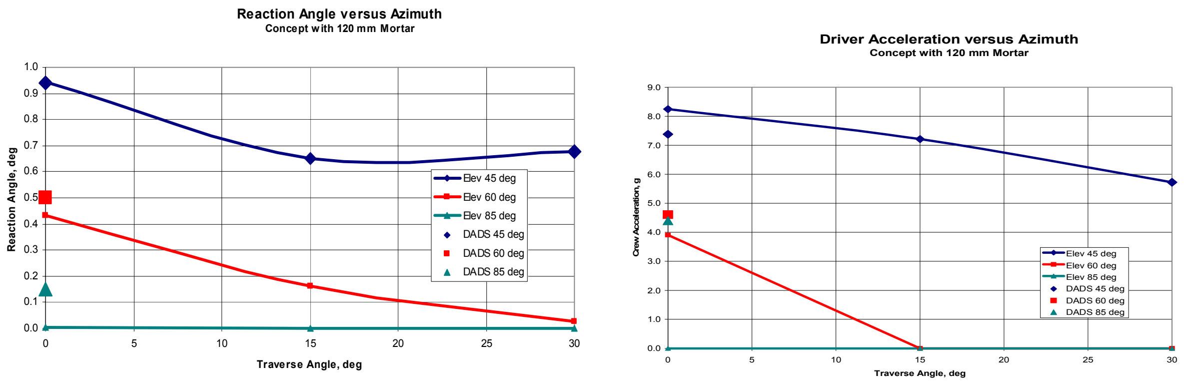

Figure 4: Notional 3-ton Vehicle Response Versus 120-mm Mortar Inputs

4.0 DETERMINATION OF FITTING FACTORS

The single-body model has a relatively low level of detail compared to other models. In addition to the lack of any spring or damper elements, the ground interface is not modeled in detail. Consequently, the models under predict reaction angle and acceleration resulting from weapon firing. To compensate for this deficiency, fitting factors are used to tune the model to better fit test data and results from more detailed analysis.

Philosophically, the fitting factors should correspond to actual phenomena that occur during firing. For the calculation of reaction angle, factors representing the sinkage of the vehicle/spade ground contact were chosen. Two factors were chosen, Sink0 for 0-degree traverse and Sink90 for 90-degree traverse. For the driver acceleration, factors representing vehicle horizontal slippage were selected. Two factors were chosen, mu0 for 0-degree traverse and mu90 for 90-degree traverse. The model interpolates between the two values based on the traverse of the cannon.

The model is tuned by selecting values for the fitting factors that minimize the difference between model and test/other analysis results. For example, Figure 4 shows curves that have been optimized to match data from a DADS simulation. Before optimization the curves under-predicted the vehicle response.

Fitting factors have been developed for several different vehicles and concepts. These vary greatly as a function of vehicle weight and other design parameters. A current area of interest is to identify the tradeoff between increased cannon performance and vehicle weight. The single-body model can be used to predict the dynamic response of a concept provided that the fitting factors can be properly selected. The approach taken is to plot the fitting factors as a function of the vehicle weight as shown in Figure 5. Curves are then fitted to the data using linear regression (with their equations shown next to them), defining an approximate relationship between the fitting factors and vehicle weight.

The dynamic response of a new vehicle concept of any weight can then be investigated using the single body model: inputs will include estimated fitting factors based on the concept weight, along with firing data for the cannon and some geometric/mass properties data for the vehicle.

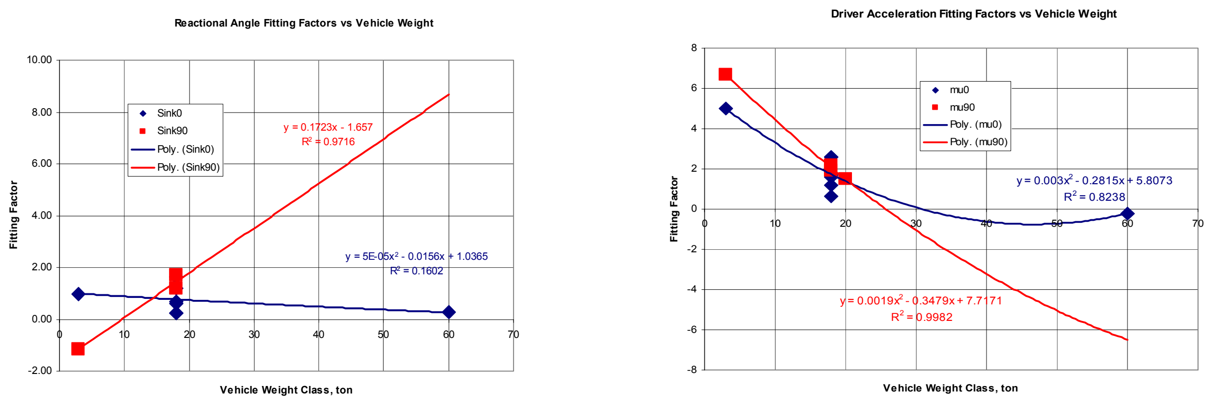

Figure 5: Fitting Factors as a Function of Vehicle Weight

5.0 TRADE STUDY OF 18-TON VEHICLES WITH 120 MM CANNONS

The single-body model approach will now be used to perform a trade study on 18-ton vehicles with 120-mm cannons and 360-degree traverse. Figure 6 shows a model of a tracked concept that had been studied at United Defense. This will be compared to a wheeled vehicle with the same cannon and combat weight.

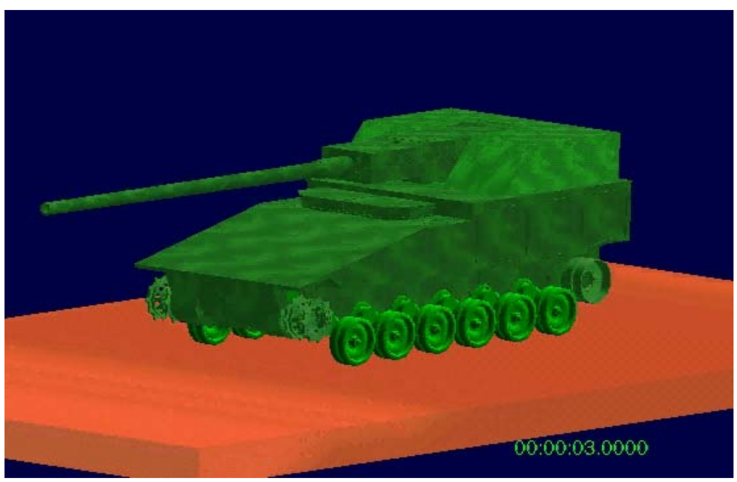

Figure 6: 18-Ton Tracked Vehicle with 120-mm Cannon

5.1 Polar Plots of Firing Response

Since the vehicle concepts have 360-degree traverse, a good approach is to calculate the cannon firing response as a function of the cannon traverse. Figures 7 and 8 show the results as polar plots showing a top view of the vehicle; this allows the display of the vehicle firing performance envelope as a function of traverse. The results are vehicle reaction angle and driver acceleration versus cannon azimuth. The simulation uses 120-mm cannon with a firing impulse of 5,700 lbf-sec and recoil stroke of 20 inches.

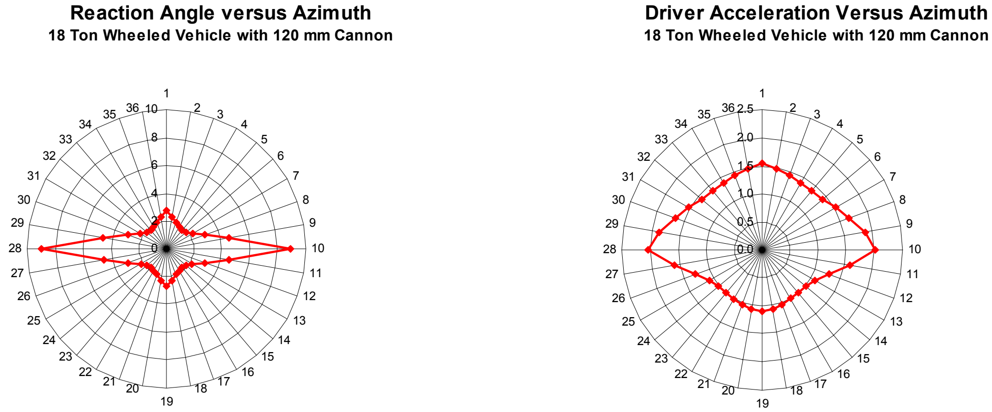

Figure 7: 18-Ton Wheeled Vehicle with 120-mm Cannon

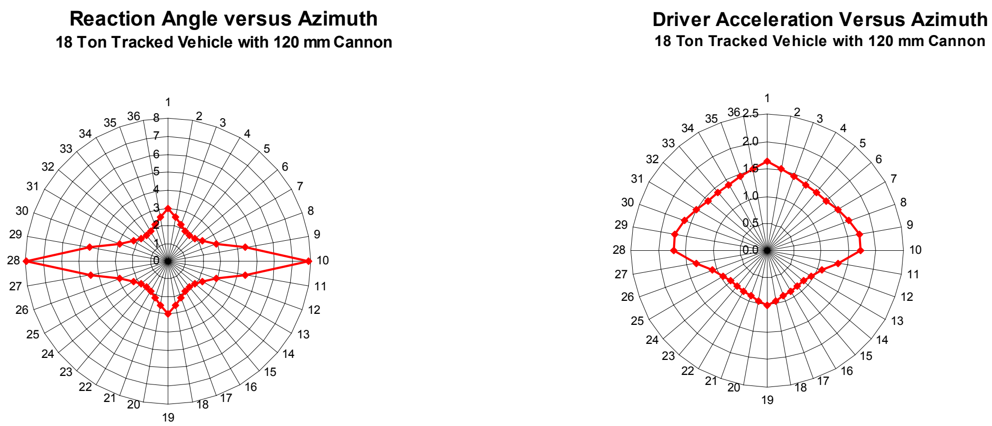

Figure 8: 18-Ton Tracked Vehicle with 120-mm Cannon

5.2 Analysis of Response for 360 Degrees Traverse

The plots show that the reaction angles increase rapidly as the cannon traverse approaches 90 degrees, due to the narrow aspect ratio of the ground footprint of the vehicles. Driver acceleration is not as affected by cannon traverse angle. The tracked design has approximately 5 percent higher reaction angle than the wheeled design, but approximately 25 percent lower driver acceleration than the wheeled design. These results indicate that the tracked vehicle is dynamically more suitable for mounting a large cannon. The differences are primarily due to the higher trunion and CG locations inherent in a wheeled vehicle design.

5.3 Comparison of Model Results with DADS Analysis

The single body model typically predicts lower pitch angles and higher roll angles than a DADS model. This is primarily due to the model assuming a rigid suspension (no springs/dampers), exaggerating the effects of the long/narrow vehicle footprint on the ground. The model typically predicts slightly higher driver accelerations than a DADS model, primarily due to the lack of suspension spring/damper elements that would reduce peak acceleration values.

6.0 CONCLUSION

The single body model has minimal input requirements and can be run very quickly to close-in on an approximate solution. This makes it well suited for rapid prototyping efforts and trend studies. The more detailed and lengthy DADS model or its equivalent can subsequently be run for more precise results, making it ideal for more detailed design of a concept. The utilization of both types of models allows the most efficient approach to modelling and analysis of light vehicles armed with high performance cannons.

References

[1] Online Tutorial, DADS (Dynamic Analysis and Design System) Basic Training (Los Angeles: LMS International, 2001).

[2] J. L. Merriam, *Dynamics, Second Edition, SI-Version* (New York: John Wiley & Sons, 1975)

[3] Dr. R. Germershausen, *Rheinmetall Handbook of Weaponry* (Dusseldorf: Rheinmetall GmbH, 1982)