APPLICATION OF LS-DYNA IN NUMERICAL ANALYSIS OF VEHICLE TRAJECTORIES

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Keywords: crashworthiness, trajectories, numerical simulation

ABSTRACT

Errant vehicles may pose a serious threat to neighboring traffic of pedestrians, bicyclists, and even to their drivers in a densely populated urban environment. Accident reconstructions have indicated that street curbs do not offer any meaningful protection against errant vehicles, which can easily traverse street curbs even at small velocity and shallow angles.

The paper presents research results of a study, in which computational mechanics was utilized to predict vehicle trajectories upon traversing standard Florida DOT street curbs. Computational analysis was performed using LS-DYNA computer code and two public domain, finite element models of motor vehicles: Ford Festiva and Ford Taurus. The suspension systems of the original vehicle models were evaluated and additional suspension components were identified and developed.

The finite element models of the required suspension systems were developed using geometry from the actual suspension parts, captured using a digitizing arm. Due to complex geometry of these parts, the MSC-PATRAN preprocessor was used to create data for LS-DYNA code. Shock absorbers were modeled using discrete spring and damper elements. Connections for the modified suspension systems were carefully designed to assure proper range of motion for the suspension models. Inertia properties of the actual vehicles were collected using tilt-table tests and were used for LS-DYNA vehicle models.

A standard FDOT street curb model was developed using rigid wall option in LS-DYNA. Initial, computational mechanics analyses suggest that vehicles tend to retain larger amount of their kinetic energy after traversing street curbs. It is therefore dangerous to anticipate that performance of street curbs would be comparable with that demonstrated by guardrails.

In order to validate the assumed discrete numerical models and the results of LS-DYNA analyses, full-scale experimental tests have been performed at Texas Transportation Institute. Two types of vehicles have been tested: Ford Festiva and Ford Taurus, both for two values of approach angle: 15 and 90 degrees, with impact velocity of 45 mph. Experimental results including accelerations, displacements and overall vehicles behavior were registered by high-speed video cameras and have been compared with numerical results and computer animations. Verification results indicated a good correlation between computational analysis and full-scale test data. The study also indicated a strong importance of properly modeled suspension and tires on resulting vehicle trajectories.

The major goal of the research was to study the behavior of various vehicles (from small Ford Festiva to pickup truck Chevrolet C2500), for different approach angles, velocities and curb profiles. Experiences gained in preliminary numerical analyses and experimental tests allow studying a matrix of critical cases without time-consuming and costly additional experimental testing.

INTRODUCTION

The increasing number of fatal accidents caused by errant vehicles, leaving their intended path and entering into areas demonstrates a need to verify the effectiveness of most popular roadside safety structures designed to separate different users of road system, i.e. street curbs and guardrails. Their performance, dimensions and configuration should protect the most vulnerable users of the road system (pedestrians and bicyclists) against contact with errant vehicles.

This is an important problem for densely populated areas, where road traffic interferes with pedestrians and bicyclists (street crossings, pavements, bike lanes, etc.). It is extremely difficult to predict all possible paths (i.e. trajectories) of errant vehicles: they depend on type of vehicle, its velocity, angle of approach, weather conditions, curb configuration and other factors. Because of these difficulties an experimental research would be impractical, very expensive and limited to a few vehicles and impact scenarios.

In order to solve this problem and to provide the designers with information regarding the effectiveness of street curbs without performing large number of expensive experimental tests, numerical analysis of vehicle trajectories have been performed using discrete formulation of finite element algorithm. This approach is now common in many practical applications, providing an efficient tool to solve problems for a large variety of its configuration (dimensions, characteristics, etc.).

Computational mechanics can be used effectively in vehicle trajectory studies if the following problems were addressed and solved:

- identifying an appropriate computer code to build a model (preprocessor), to perform all necessary calculation (solver), and to analyze the results (postprocessor);
- creating a reliable finite element model of the structure, with necessary assumptions and simplifications, in order to have a computer model as simple as possible to achieve reliable results;
- assumption of parameters necessary to control the analysis: global damping, contact description, hourglass control, etc., depending on the numerical algorithms applied in analysis;
- choice of possible problem configuration;
- choice of data to be compared in analyses.

The following two vehicles were considered for this trajectory studies:

- a small car: Ford Festiva;
- a mid-size car: Ford Taurus;

These cars represent popular classes of vehicles, because of their weight, dimensions and characteristics of suspensions. However, techniques described in this paper could be used to develop discrete models of other vehicles. The limit 45 mph of maximum velocity has been assumed in all cases, as well as two different approach angles: 15 and 90 degrees. These angles represent two different situations: a very small approach angle (15 degrees), which leads to almost parallel entrance to the sidewalk next to the roadway, and an impact perpendicular to a curb (90 degrees).

LS-DYNA [1] explicit finite difference computer code has been used for this trajectory studies. This computer code is especially popular in automotive applications because of its stability and many features developed to solve specific problems common in vehicle dynamics: variety of available finite element types, material models, contact definitions and additional features useful for modeling joints, constraints and time-dependent boundary conditions. In spite of the code consistency and efficiency, a LS-DYNA user should have sufficient knowledge to deal with explicit analysis algorithm, in order to obtain reliable results. Conditional convergence of algorithm provides for the drastic reduction of the time step with increased number of finite elements used to build the discrete model. This leads to the significant increase of computation time. Thus it is necessary to find a proper relation between the complexity of assumed discrete model and time necessary to perform calculation.
Application of modern preprocessors like MSC PATRAN [2] make the whole process of building the entire discrete model much easier, despite of many LS-DYNA features, which were not supported by MSC PATRAN.

APPROACH

Public-domain finite element models of Ford Festiva and Ford Taurus [8] have been adopted and then modified in order to retrofit them with reliable suspensions and wheels, with data collected from experimental tests (dampers and springs) or numerical analysis (tires). The fundamental importance of suspension characteristics on vehicle's behavior after traversing the curb is well-recognized and described in literature [3-5]. Figures 1 and 2 provide basic information about assumed discrete models for the vehicles, which were used in this study.

All discrete models are built with only three material formulations:

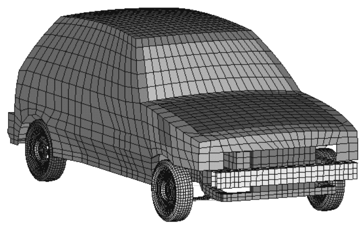
- rigid;
- linear-elastic;
- elasto-plastic von Mises nonlinear model, with hardening.

For many parts of vehicles (suspensions, body, etc) the elasto-plastic material model have been replaced in final analyses by a rigid one, due to obvious lack of plastic deformation in these parts during traversing the curb. This approach gives the reduction of time necessary to perform entire analysis, and also reduces undesirable hourglass effects in shell elements.

In order to model contact between vehicle and surfaces of roadway, curb and sidewalk the adequate set of rigid walls have been created. Since the gravity load is applied instantaneously, the position of vehicle has been adjusted carefully to avoid extensive initial vibrations due to initial penetration of nodes or lack of contact between tires and rigid wall. An orthogonal friction model has been adopted in order to describe the interaction between tires and roadway. Parameters of friction were studied and assumed on the basis of earlier studies [6,7]. In order to avoid additional penetration for elements of tires through rims, etc., contact has been assumed between rims and tires. This was especially important for tests with approach angle 90 degrees, where tires have been subjected to extremely large deformations resulting in a contact with wheel rims.

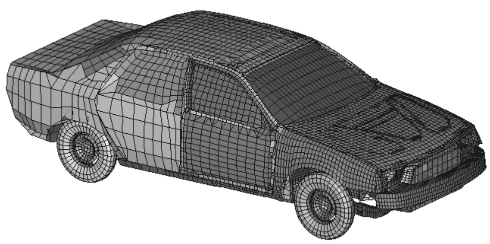
Spring and dampers in suspensions have been modeled with adequate discrete elements. In order to simulate the presence of steering system, additional rotational springs and dampers have been assumed. This lead to more stable (i.e. realistic) behavior of front suspension under dynamic loads exerted during impact against the curb. Although the values of characteristics for rotation springs and dampers have been assumed arbitrarily on the basis of numerical tests, the entire system is stable and keeps the assumed direction of movement.

Constant velocity of 45 mph was achieved by assuming the initial translational velocity for entire body of the vehicle, and additional initial rotational velocity for wheels. Although there are no other constraints imposed on vehicle's motion after initial time t=0, the changes in translational velocity on the distance to the curb are very small, and can be neglected. It is reasonable to assume that the translational velocity for the vehicle is constant until the first wheel reaches the curb.



Ford Festiva
Total number of elements: 15,769
Beam elements: 62
Shell elements: 13,163
Solid elements: 2,545

Figure 1. Finite element discrete model of Ford Festiva



Ford Taurus
Total number of elements: 37,381
Beam elements: 102
Shell elements: 30,749
Solid elements: 6,530

Figure 2. Finite element discrete model of Ford Taurus

DISCUSSION OF RESULTS

The following components of vehicle trajectories have been studied to validate data from numerical analysis with the corresponding experimental results:

a) accelerations of the center of gravity;
b) displacements of points located on the vehicle's body;
c) overall dynamic behavior of vehicle's body registered on a video.

Although the final report on experimental tests [9] contain more detailed information on vehicle's behavior during the tests, the characteristics mentioned above are of the fundamental importance, and should be considered as a primary validation process of assumed discrete models. Accelerations in discrete model have been calculated by interpolation between values for nodes closest to the position of vehicle's center of gravity. The same technique has been adopted for points located on the vehicle body. Special attention has to be paid to the analysis of velocity of vehicle after crossing the curb, in order to compare the reduction of kinetic energy due to impact effects. This velocity can be evaluated for the points on the body (calculated from displacements), or for the center of gravity (integration of linear accelerations). This second approach seems to be more accurate, due to approximate functions of displacements in time (films from high-speed cameras were analyzed on a computer-linked Motion Analyzer).

Ford Festiva, approach angle 15°

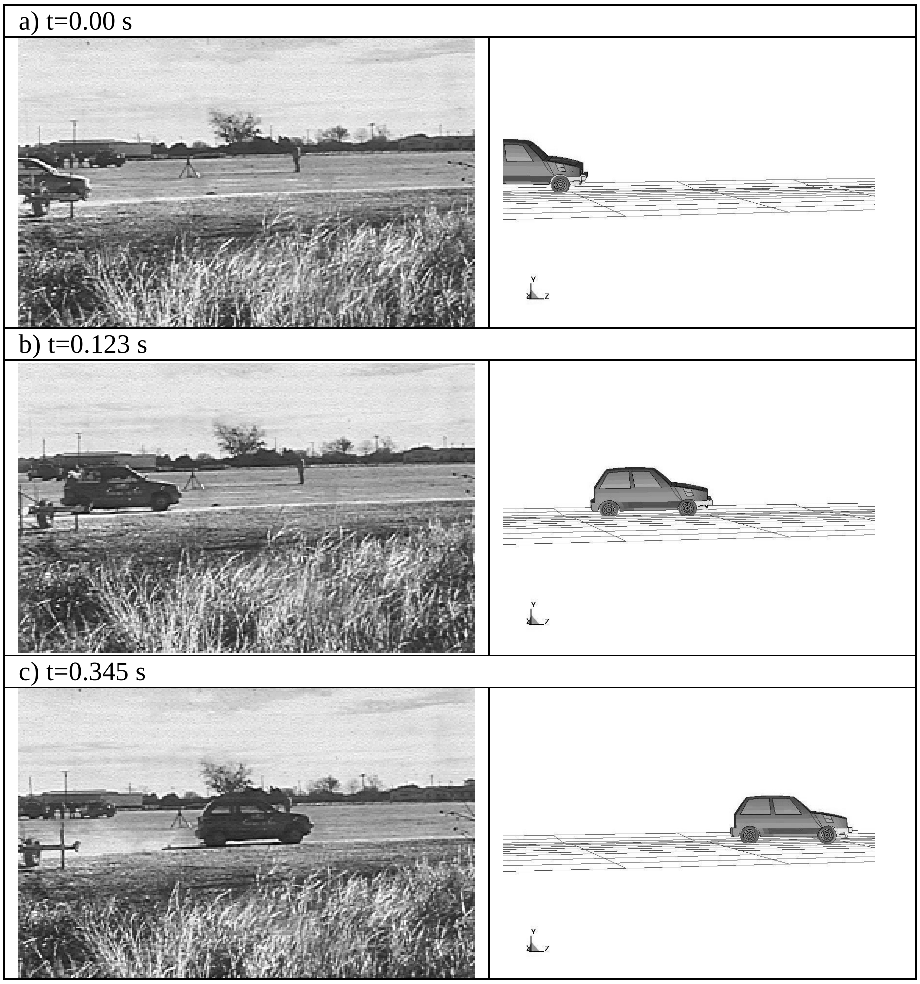


Figure 3. Ford Festiva – approach angle 15°

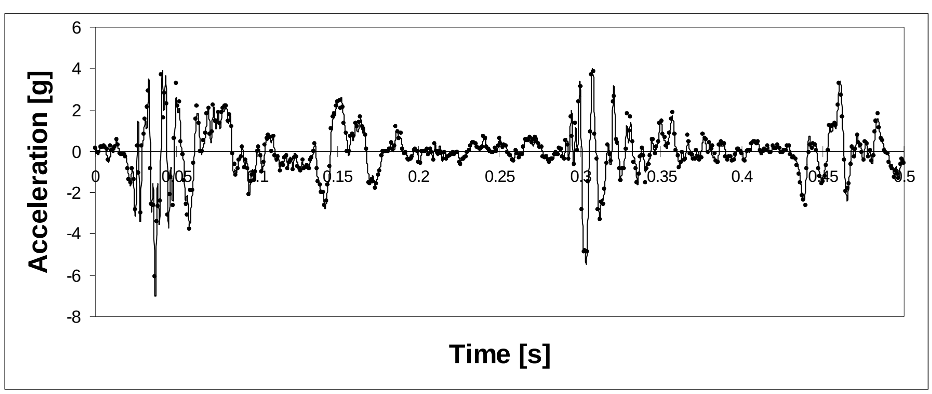
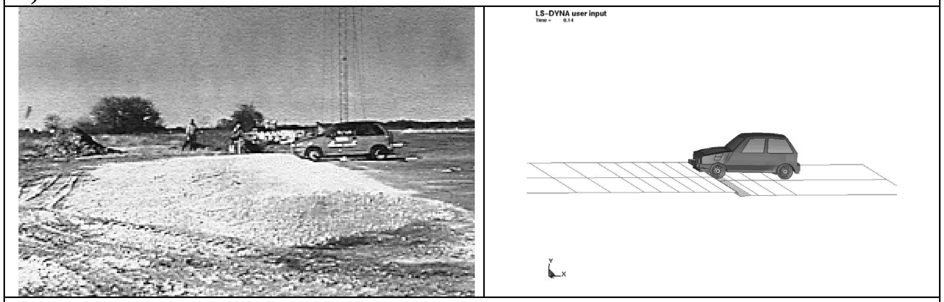


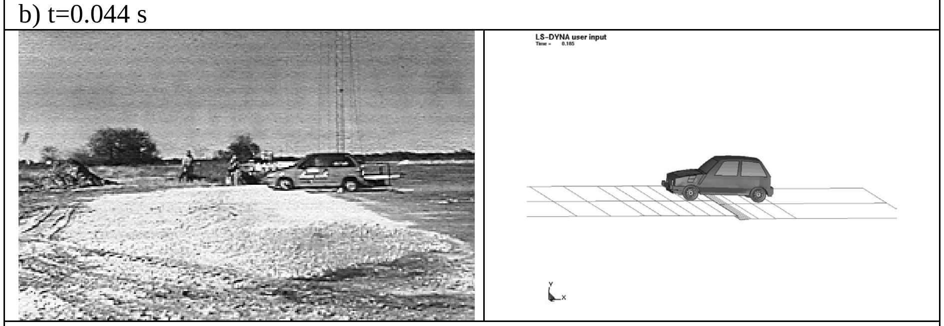
Figure 4. Ford Festiva – approach angle 15°. Longitudinal acceleration (in g) for the vehicle gravity center. (Continuous line – experiment, discrete points – simulation)

Ford Festiva, approach angle 90^o

a) t=0.00 s



b) t=0.044 s



c) t=0.198 s

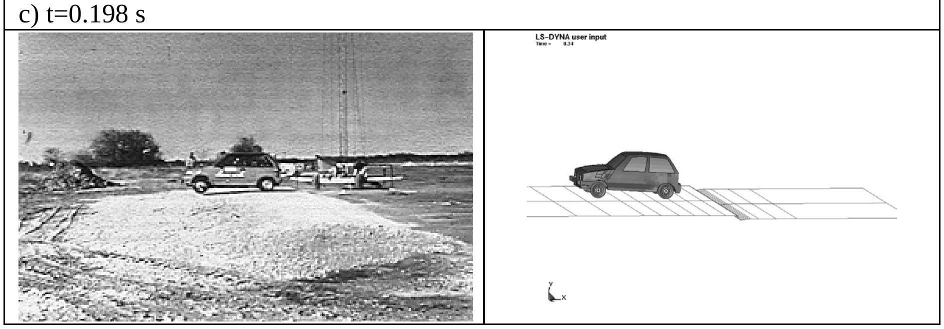


Figure 5. Ford Festiva – approach angle 90^o

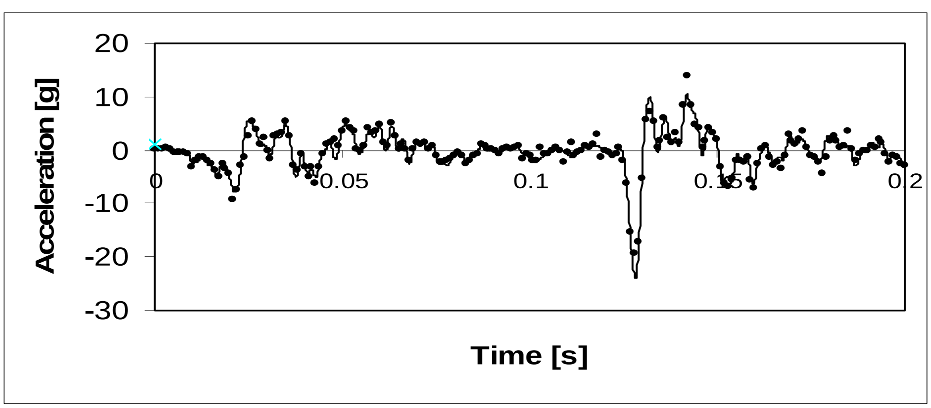


Figure 6. Ford Festiva – approach angle 90^o. Longitudinal acceleration for the gravity center.
(Continuous line – experiment, discrete points – simulation)

Similar results have been obtained for Ford Taurus, in terms of vehicle's overall behavior and accelerations. Comparison of results for all four cases considered shows a good correlation of numerical data with experimental results. It helps in gaining a higher confidence level for other quantities describing the overall vehicle's behavior, i.e.: velocities and displacements for points located on vehicle's body and for center of gravity. The examples of such analyses for Ford Festiva are given below.

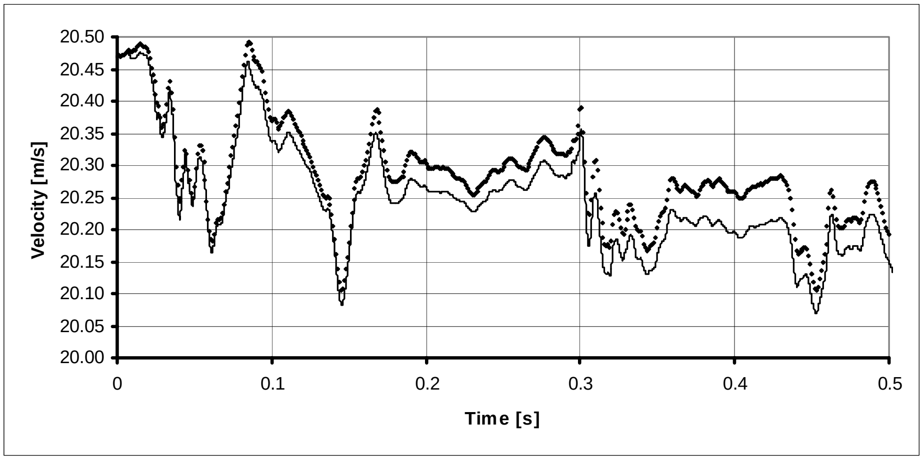


Figure 7. Ford Festiva – approach angle 15°. Longitudinal velocity for the gravity center. (Continuous line – experiment, discrete points – simulation)

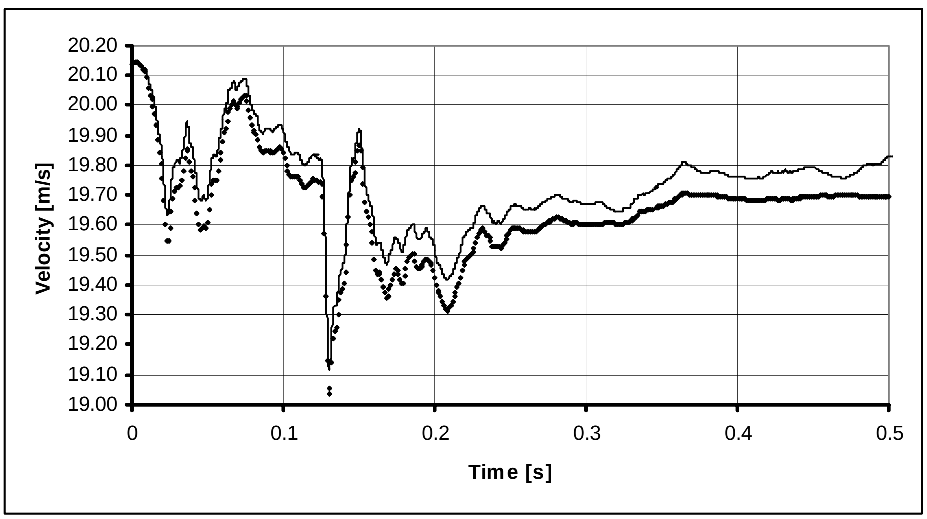


Figure 8. Ford Festiva – approach angle 90°. Longitudinal velocity for the gravity center. (Continuous line – experiment, discrete points – simulation)

Very good correlation between experimental and numerical data has been obtained for both: 15° and 90° approach angles for Ford Festiva. Similar comparison for Ford Taurus resulted in bigger discrepancies, due to much more complicated kinematics of front suspensions. This latter case has to be studied yet.

CONCLUSIONS

This paper presents examples of a study of a complex real-life problem, where computational mechanics allows for an interesting parametric study, which captures characteristics important for roadside safety. Discrete finite element models were implemented in this project in order to study velocities, street profiles, approach angles, friction between tires and road surface, etc.

Experimental tests, performed for a selected few configurations, served as a final validation of the discrete models and methodology of computational mechanics assumed. The validated discrete models of the vehicles allowed for further analytical studies, where the overall vehicle kinematics played a decisive role. The results obtained from this research indicated that vehicles tend to retain larger amount of their initial kinetic energy after traversing a street curb. Therefore, street curbs should never be considered as guardrails, shielding pedestrians from errant vehicles. Smaller vehicles, impacting street curbs at shallow angles, appear to be also dangerous, as shown in preliminary studies.

Methodology of building the discrete model, assumptions regarding types of finite elements, material models, constraints and initial conditions have been checked and studied, in order to make numerical analyses reliable and efficient.

ACKNOWLEDGMENTS

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation, nor the U.S. Department of Transportation. This publication was prepared in cooperation with the State of Florida Department of Transportation under Project No. BC352 (Project Manager: Mr. Thomas Bane, P.E.). Technical assistance and guidance provided by Mr. Bane during this study is appreciated. Authors would like to acknowledge the financial support of the Florida Department of Transportation, which made this research project possible.

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