Vehicle trajectories resulting from traversing FDOT street curb Numerical analysis and experimental verification

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Abstract

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 [1] computer code and two modified public domain finite element models of motor vehicles: Ford Festiva and Ford Taurus. Computational mechanics analyses indicated that both 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. Full-scale experimental tests for Ford Festiva and Ford Taurus have been performed at Texas Transportation Institute to validate the assumed discrete numerical models and the results of LS-DYNA analyses. Both vehicles have been tested for two values of approach angle, with impact velocity of 20 m/s (72 km/h). The numerical study indicated a strong dependence of vehicle trajectories on properly assumed discrete model for suspension and tires. The major goal of the further research was to study the behaviour of various vehicles (including heavier Chevrolet pickup-truck) for different approach angles, velocities and curb profiles.

Keywords – dynamics, impact, trajectories, explicit analysis

1. Introduction

The increasing number of fatal accidents caused by errant vehicles leaving their path and entering unintended 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 design, 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.

Numerical analysis of vehicle trajectories have been performed using discrete formulation of finite element algorithm to aid designers with information regarding the effectiveness of street curbs without performing large number of expensive experimental tests. This approach is becoming common in many practical applications, providing an efficient tool to solve problems for a large variety of contact-impact problems. 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 analyse the results (postprocessor);
- building a reliable finite element model of the system, with necessary assumptions and simplifications, resulting in as simple as possible discrete model yet 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, in NCHRP Report 350, [10]:

- 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 20 m/s 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 particularly popular in automotive and highway safety 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 modelling 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.

2. Approach

Public-domain finite element models of Ford Festiva and Ford Taurus [8] have been adopted and modified with reliable models of suspensions and wheels. Material properties for these models were collected from experimental tests (dampers and springs) or numerical analysis (tires). Fundamental dependence of vehicle's behaviour after traversing the curb on suspension characteristics 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 Misses nonlinear model, with hardening.

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

A set of rigid wall models has been designed to model contact between vehicle and surfaces of roadway, curb and sidewalk. Since the gravity load is applied instantaneously, the position of vehicle has been adjusted 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 interaction between tires and roadway. Friction parameters were adopted from earlier studies [6,7]. Contact between rims and tires has been modelled to avoid penetration of tire elements through rims. This was especially important for tests with approach angle of 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 simple but reliable discrete elements. Additional rotational springs and dampers have been assumed to simulate steering system for both vehicle models. This led to more stable (i.e. realistic) behaviour 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 based on numerical tests, the entire system was stable and maintained the assumed path of the vehicle.

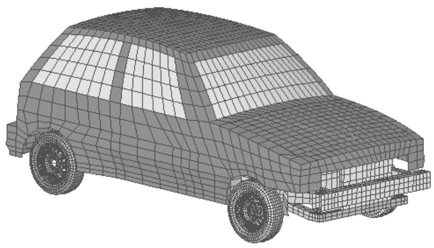

Fig. 1 – Finite element model of Ford Festiva(15 769 elements)

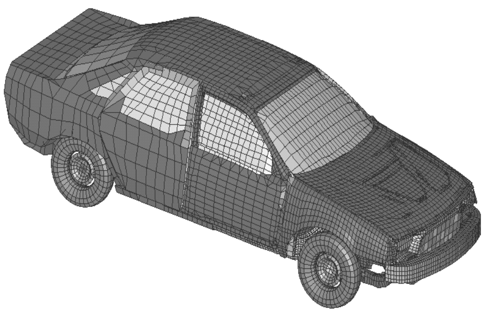

Fig. 2 – Finite element model of Ford Taurus (37 381elements)

Constant velocity of 20 m/s (72 km/h) was achieved by assuming the initial translational velocity for entire body of the vehicle, and corresponding 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 contacts the curb.

3. Experimental verification

The purpose of this part of the project was to perform full-scale trajectory testing using 1992 Ford Festiva and 1991 Ford Taurus on a segment of FDOT Type F curb. External high speed video and internal electronic instrumentation placed inside the vehicles provided information on vehicle trajectories for each test. This data acquisition system provided time histories of acceleration and angular velocities for the vehicle's centre of gravity. In addition, longitudinal and vertical time histories of displacements for selected points on each vehicle were recorded from the high speed film. This data were used to compare with similar data obtained from computational mechanics efforts.

3.1 Test facility

Validation testing program was designed and performed at Texas Transportation Institute in January 2002. The site selected for installation of the FDOT Type F curb was along a wide out-of-service apron. The apron consisted of an unreinforced jointed concrete pavement in 3.8 by 4.6 m blocks (as shown in Figure 4) nominally 203-305 mm deep.

3.2 Test article

A length of 22.9 meters of FDOT Type F curb was constructed (Figure 3-4). The curb incorporates a 150 mm high curb with a sloping concrete gutter. The curb was 150 mm wide at the top. The width of the curb at the base of the gutter was 200 mm. The face of the curb sloped back from the gutter on a 1 (horizontal) to 3 (vertical) degree slope. The overall width of the curb including the gutter was 600 mm. The Type F curb was constructed adjacent to an existing 203 mm thick concrete apron. The curb was rigidly attached to the apron with 13 dowels, which extended into the curb. These dowels were located 610 mm apart and were epoxy anchored into the existing concrete apron. The curb was supported by 150 mm of compacted crush stone. Compacted crush stone was placed in lifts behind the curb to simulate a 1829 mm wide sidewalk. The sidewalk was flush with the top of the curb. The entire curb and sidewalk setup is shown in Figure 4.

3.3 Test conditions

The following four trajectory tests were specified to provide vehicle trajectory data for validation of the F.E. models developed:

- Test No. 1 - Ford Festiva, 15 degrees. The test involved a 1992 Ford Festiva impacting the type F curb at a nominal speed of 20 m/s at an impact angle of 15 degrees.
- Test No. 2 - Ford Festiva, 90 degrees. The test involved reused Ford Festiva from Test No. 1 and impacting the type F curb at a nominal speed of 20 m/s at an angle of 90 degrees (perpendicular to the curb installation).

Fig. 3 – FDOT Type F curb and test site prepared to test No.1

Fig. 4 – FDOT Type F curb prior to testing (Test No. 1)

- Test No. 3 - Ford Taurus, 15 degrees. The test involved a 1991 Ford Taurus impacting the type F curb at a nominal speed of 20 m/s at an impact angle of 15 degrees.
- Test No. 4 - Ford Taurus, 90 degrees. The test involved reused Ford Taurus from Test No. 3 and impacting the type F curb at a nominal speed of 20 m/s at an angle of 90 degrees (perpendicular to the curb installation).

The crash test and data analysis procedures were in accordance with guidelines presented in National Cooperative Highway Research Program (NCHRP) Report 350 [10].

4. Discussion of results

The following time histories 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 behaviour of vehicle's body registered on a video.

Although the final report on experimental tests [9] contained more detailed information on vehicle's behaviour during the tests, the characteristics listed above were of the fundamental importance, and they were included as a primary source of information for validation of the assumed discrete models. Accelerations of discrete models 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 been paid to the analysis of velocity of vehicle after traversing the curb, in order to assess kinetic energy dissipated when vehicles wheels impacted street curbs. This velocity was evaluated for the points on the body (calculated from displacements), or for the center of gravity (integration of linear accelerations). The second approach appeared to be more accurate, due to approximate functions of displacements in time (films from high-speed cameras were analysed on a computer-linked Motion Analyser).

Very good correlation between experimental and numerical data has been obtained for both: 15^{o} and 90^{o} approach angles for Ford Festiva. The overall behaviour of vehicle observed during the experiment was virtually the same as in numerical analyses, in terms of body behaviour, kinematics of suspensions, etc. Figures 5 and 6 present, respectively, the images from the Test No 1 and corresponding numerical analysis.

Fig. 5 – Ford Festiva – approach angle 15^{o} (time t=0.123 s). High-speed camera recorded image.

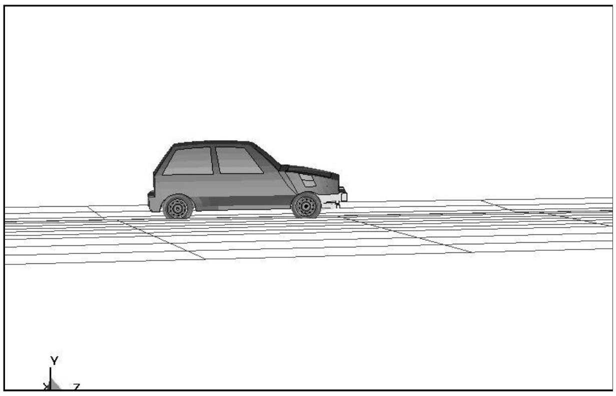

Fig. 6 – Ford Festiva – approach angle 15^{o} (time t=0.123 s). LS-DYNA simulation.

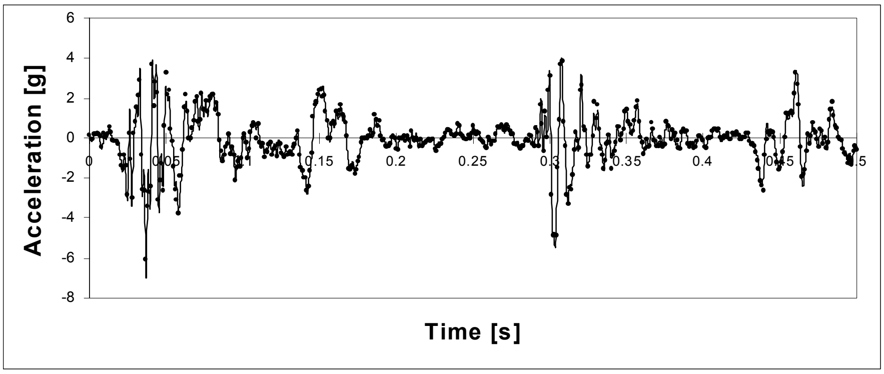

Fig. 7 – Ford Festiva approach angle 15°. Longitudinal acceleration (in g) for the vehicle gravity center. (Continuous line – experiment, discrete points – simulation)

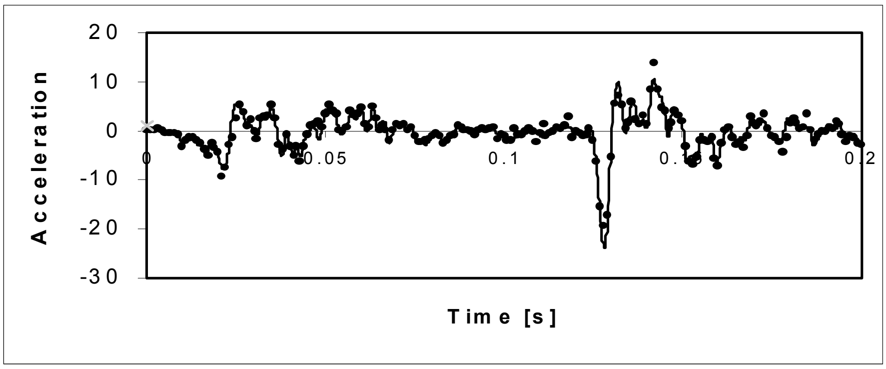

Fig. 8 – Ford Festiva approach angle 90°. Longitudinal acceleration for the gravity center. (Continuous line – experiment, discrete points – simulation)

The only differences occurred in final stage of tests due to the limited area of reinforced pavement prepared at the test site.

Accelerations of the center of gravity (Figures 7 and 8) represented a high correlation between experimental and numerical results.

Four local peaks of longitudinal (i.e. parallel to the longitudinal axis of the vehicle) accelerations are clearly visible in Figure 6 (approximately t = 0.05, 0.15, 0.3, 0.45 s), due to the subsequent impacts of four wheels on the curb.

Peaks in Figure 7 are also easy to identify, but their distribution is less obvious. Two zones of bigger peaks (first between 0.025 and 0.05, second between 0.125 and 0.15) resulted from direct impact of front and rear wheels on the curb, while smaller peaks were due to swing motion of entire body during traversing the curb.

Similar correlation can be observed in Figures 9 and 10, where the longitudinal velocities were plotted as a function of time.

The difference between numerical and experimental results has tendency to increase in time, due to the applied method of velocity calculation (integration of accelerations). Also in this case, discrepancies between tests and analyses were very small (Table 1).

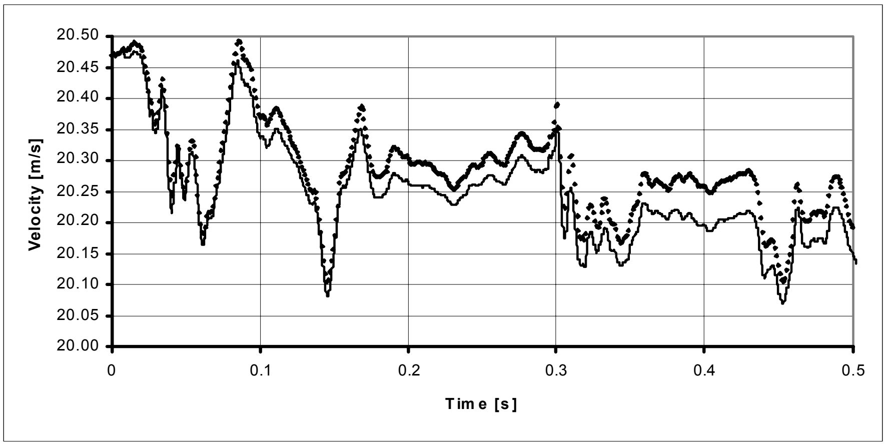

Fig. 9 – Ford Festiva – approach angle 15^o. Longitudinal velocity for the gravity center. (Continuous line – experiment, discrete points – simulation)

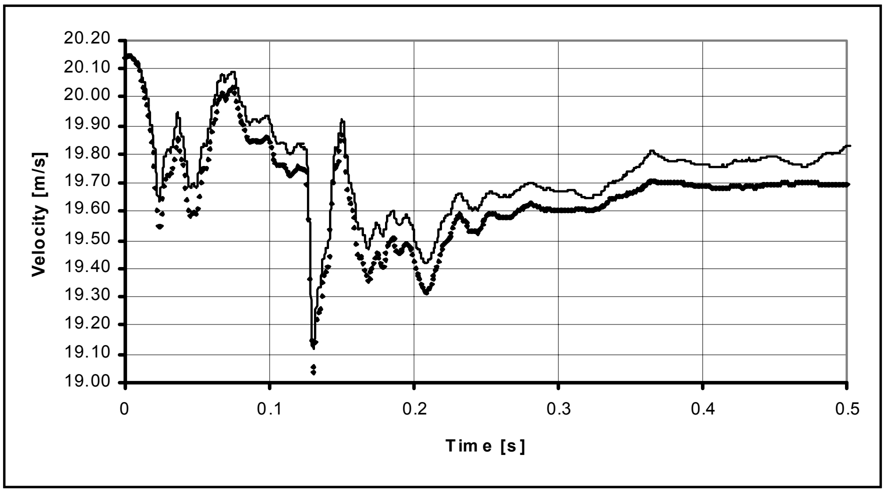

Fig. 10 – Ford Festiva – approach angle 90^o. Longitudinal velocity for the gravity center. (Continuous line – experiment, discrete points – simulation)

Information on overall trajectory of the selected points of vehicle's body can provide invaluable information for roadside design engineers. It is especially true if two points on both ends of the front bumpers are selected.

Trajectories of these two points help to determine possible location and heights of the guardrails. Figures 11 and 12 illustrate paths of the front bumper ends, which were plotted in front and upper view, respectively.

Figure 13 depicts a trajectory of the right corner of the front bumper of Ford Festiva. The trajectory is shown together with the FDOT curb (F type) profile, for the approach angle 15 degrees. Peaks of this plot indicate possible placement and heights of guardrails or other types of barriers, protecting other users of pavement against contact with errant vehicles.

Tab. 1 – Reduction of initial speed and kinetic energy

	EXPERIMENT				NUMERICAL ANALYSIS			
Vehicle (impact angle)	Impact speed (m/s)	Exit speed (m/s)	Reduction of speed (%)	Reduction of kinetic energy (%)	Impact speed (m/s)	Exit speed (m/s)	Reduction of speed (%)	Reduction of kinetic energy (%)
Festiva (15º)	20.61	20.19	**2.04**	**4.06**	20.61	20.13	**2.32**	**4.57**
Festiva (90º)	20.27	19.81	**2.29**	**4.52**	20.27	19.73	**2.67**	**5.29**
Taurus (15º)	20.47	19.71	**3.70**	**7.25**	20.47	20.03	**2.18**	**4.31**
Taurus (90º)	20.50	19.26	**6.00**	**11.65**	20.50	18.12	**11.61**	**21.88**

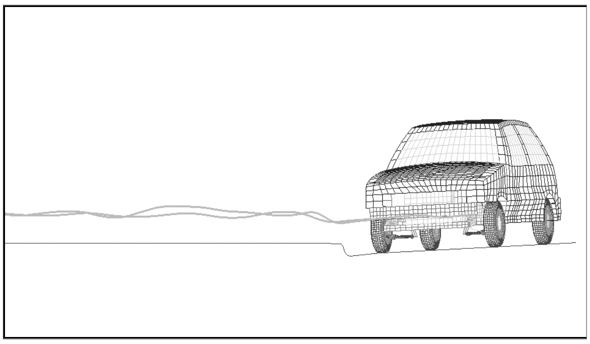

Fig. 11 – Trajectories of the bumper ends. Front view. (Ford Festiva, 15 degrees)

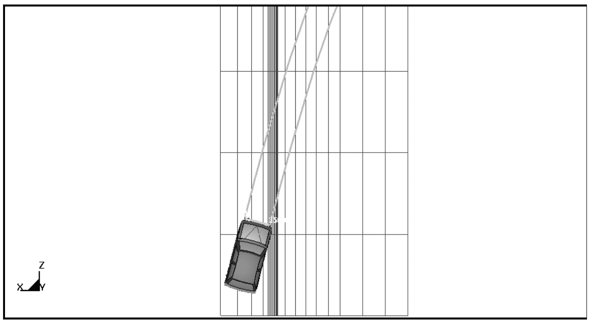

Fig. 12 – Trajectories of the bumper ends. Upper view. (Ford Festiva, 15 degrees)

Trajectory analyses and tests provided additional information about vehicle's behaviour given in [13]. This data includes:

- longitudinal, vertical and transversal displacement of the right end of the front bumper;
- longitudinal, vertical and transversal velocity of the right end of the front bumper;
- an approach angle at which the vehicle does not traverse the curb, but rather bounces back from it.

Longitudinal, vertical and transversal components of each vehicle path were measured with respect to the curb and were provided in [13]. This information allowed for synthesis of all possible cases of vehicle paths depending on the vehicle type, its speed, and approach angle.

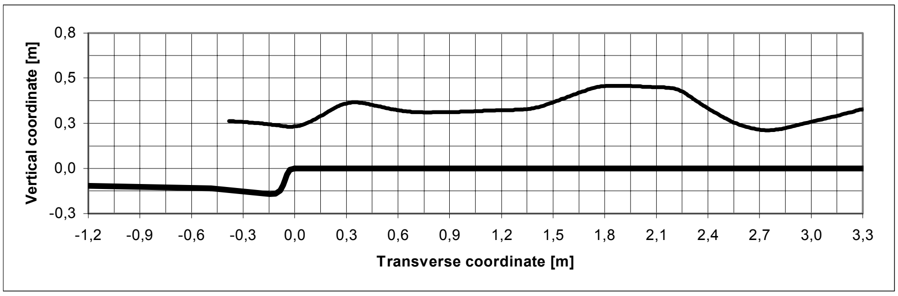

Fig. 13 – Trajectory of the bumper right corner (Ford Festiva, 15 degrees)

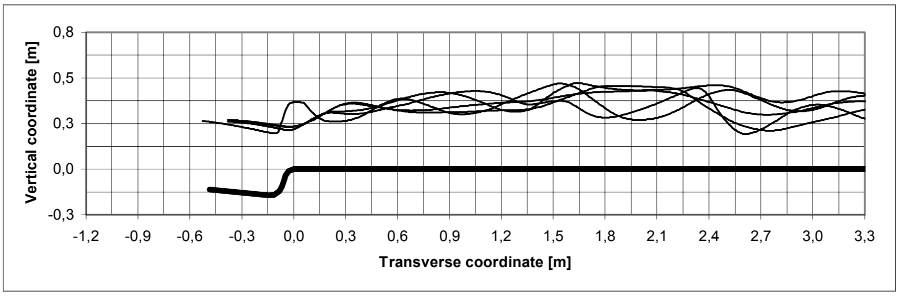

Fig. 14 – Whole set of trajectories – Ford Festiva

Figure 14 illustrates the entire set of trajectories of the right end of the front bumper for Ford Festiva, obtained for following parameters:

- velocities: 55, 72 and 88 km/h;
- approach angles:12^o, 15^o

For approach angles lower than 12^o Ford Festiva did not traverse the street curb. This behaviour did not appear to depend on vehicle's velocity and other parameters as the friction between tires and pavement. Similar comparison for Ford Taurus resulted in bigger discrepancies, due to much more complicated kinematics of front and rear suspensions [12]. Since the target analyses of the entire set of possible approach angles, curb, roadway configurations, and velocities were limited to small Ford Festiva and Chevrolet pickup truck [13], the results for Ford Taurus have been accepted as qualitative only, without further modifications of discrete model.

Table 1 shows the comparison between experimental and numerical results of reduction of initial speed and kinetic energy of both vehicles before – and after – traversing the FDOT Type F street curbs.

5. Conclusions

This paper presents examples of a study of a complex real-life problem, where computational mechanics allowed for an interesting parametric study, which captured 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. Four 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 this study. Methodology of developing discrete F.E. models, types of finite elements assumed, material models, constraints and initial conditions have been checked and studied in order to make numerical analyses reliable, efficient and useful for highway engineers.

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