Using Finite Element Structural Analysis of Retroreflective Raised Pavement Markers (RRPMs) to Recommend Testing Procedures for Simulating Field Performance of RRPMs

A Thesis Proposal

By

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INTRODUCTION
Retroreflective raised pavement markers (RRPMs) are used for providing delineation on highways. The Manual on Uniform Traffic Control Devices (1) defines a raised pavement marker (RPM) as “a device with a height of at least 10 mm (0.4 in) mounted on or in a road surface that is intended to be used as a positioning guide or to supplement or substitute for pavement markings or to mark the position of a fire hydrant”. They are especially useful in nighttime and in rainy conditions when the pavement markings lose their effectiveness to provide guidance to drivers. In addition, the rumbling effect of RRPMs reminds drivers to remain in their lanes.

The performance of RRPMs in some states has been degrading over the years. Two major problems associated with the RRPMs are lower retention on pavements and loss of retroreflectivity. An effective ‘RRPM system’ would have markers remain in the installed locations and have sufficient retroreflectivity over time. However, it has been found that markers lose most of their effectiveness on high volume highways in a short time after installation because of poor retention and durability. Marker failure can happen in many forms: breaking of marker body or lens, adhesive failure (loss of markers from the pavements) and loss of retroreflectivity. Various factors that can account for these failures are high traffic, severe loading (as from trucks), sand abrasion and environmental factors like ultra-violet radiation. It is believed by several research agencies that poor manufacturing and inadequate application may have contributed to the decrease in the durability of markers as well.

PROBLEM STATEMENT
One of the main causes for the underperformance of RRPMs is the lack of appropriate laboratory testing standards, which could test the adequacy of the RRPMs to perform in field conditions. The existing testing standards are either inadequate for simulating the real world conditions in the laboratory or do not test the RRPMs to their limits (2). There is a need to modify the existing standards or develop new testing procedures that could simulate the field conditions better. This requires identifying critical locations and magnitudes of forces inside the markers during the tire-marker impacts in the field. While the previous studies mainly tried to find out the factors affecting the performance of RRPMs, little work has been carried out in finding the locations and
magnitudes of stresses generated in markers during the tire-marker impacts. Measuring these stresses multiple times (including various factors) in the field is not feasible.

A finite element computer modeling, simulation and analysis of the tire-markers impacts should be carried out to give information on the locations and magnitudes of stresses during the impacts. A computer simulation gives the flexibility to analyze the tire-marker impacts with different factors, which would not be practical in the field. In addition, it is time and cost efficient. This research is designed to apply the finite element computational techniques for the analysis of tire-marker impacts in real world conditions.

**BACKGROUND**

This section of the proposal provides information on the previous research gone into finding causes behind deterioration of durability of RRPMs. The section also provides background information on finite element analysis and its applicability in understanding tire-marker impacts.

**Previous Research on Durability of Markers**

Not much research has gone into the causes of deterioration of performance of RRPMs. Studies conducted at Texas Transportation Institute (3, 4, 5, 6) revealed that RRPMs lose a significant amount of their initial retroreflectivity within two years. They concluded that heavy volume and high truck traffic were the major factors causing the loss of retroreflectivity and poor retention in markers (3, 4, 5, 6). The loss of markers was due primarily to their inability to repeatedly absorb the total force imposed on them and transmit it to the pavement.

In a subsequent study, Tielking and Noel (7) performed a study of tire-marker impacts, which revealed that the most damaging impact on markers occurs when the side wall of tire strikes a glancing blow on the more vertical side (non-retroreflective, parallel to traffic) of a marker, such as would be experienced during a turning-passing maneuver. Here the maximum force will tend to displace the marker laterally, twist it about its vertical axis and rotate it about its longitudinal (traffic direction) axis (7). One of the critical conditions for pavement, in terms of negative moments produced, is the application of a vertical force on the edge of the non-reflectorized side. Assuming marker to be completely rigid and perfectly attached to the surface of the pavement, the pavement force pattern is like a uniform load of P/4 (assuming 4x4 inch marker; P is the tire
force) and a triangular load of M (caused by the moment at the centre of the marker) on the marker top (Figure 1).

The researchers also did a high-speed photography of tire-marker impacts. It was found that a small high-pressure car tire did not bound over the marker but instead stayed in contact over entire top surface of the marker and remained in contact over a portion of the sloping exit surface. It was also found that a truck tire might stay on top of a marker longer than a passenger car tire would (7). This suggests that truck loading may be a critical factor in marker durability.

![Figure 1. One Critical Force Condition (7)](image)

Few researchers have tried to find out the causes behind decay of retroreflectivity of RRPMs. A study on RRPMs retroreflectivity concluded that glass faced markers would perform better than plastic faced markers (8). Ullman (9, 10, 11) did a two-year evaluation of retroreflectivity of RRPMs in Texas and tried to co-relate the field and laboratory tests measurements of retroreflectivities. He found that loss of retroreflectivity was largely dependent on the number of tire impacts, which is a function of Average Daily Traffic (ADT), and truck traffic.

**Finite Element Analysis**

Finite element analysis (FEA) is a method for analyzing a complex structure under stresses. This employs numerical techniques to solve boundary-value problems. The real object or system in finite element analysis is represented by a geometrically similar and simplified model consisting of multiple linked finite elements (12). Equations of equilibrium together with compatibility and constitutive relations are applied to each element. A system of simultaneous equations is
constructed which is solved for unknown values using linear or non-linear numerical techniques (12). FEA is generally used for the determination of stresses and displacements in mechanical objects and systems (12).

The finite element analysis is generally done with the help of finite element modeling and solving software. Hypermesh is a finite element pre-processor and post-processor for finite element analysis applications (13). The software can be used to design and analyze tire-marker impacts in a highly interactive visual environment. It supports major finite element solvers like LS DYNA. The LS-DYNA is a non-linear finite element program capable of simulating complex real world problems (14). Its major applications lie in the crash modeling, metal forming and cutting, earthquake engineering etc. It can work on many material models including rubber and plastic polymers.

**RESEARCH OBJECTIVES**

The goal of this research is to identify the critical magnitudes and locations of stresses in retroreflective raised pavement markers (RRPMs) from finite element computer simulation of tires-markers impacts and use the information to recommend testing procedures that could simulate the real-world conditions. The research objectives are:

- To model the tire-marker system using finite element tools and to calibrate the model,
- To use the model to simulate the real-world tire-impact forces on markers and find the critical locations and magnitudes of stresses,
- To vary the external loading conditions and analyze the effect of varying loads, velocities, locations of impact and angles of impact on magnitudes, and locations of forces in markers, and
- To recommend laboratory testing procedures that could simulate the field performance of retroreflective raised pavement markers based on the results.

**RESEARCH BENEFITS**

This research work is being done to compliment a Texas Department of Transportation project that deals with improving the laboratory testing procedures for RRPMs so that the laboratory tests could reflect the actual field conditions of markers. The project plans to develop
specifications, testing procedures and application guidelines to get appropriate functionality and service life from RRPMs. The results of this research will provide insights into the critical locations and magnitudes of the forces inside the markers. That will help identifying the laboratory tests, which could simulate the actual field conditions in the laboratory environment.

RESEARCH METHODOLOGY
The various tasks to be done as a part of the research are discussed below:

Task 1: Literature Review
As a part of this task, the researcher will conduct a review of the state-of-the-art concerning durability of markers. As stated earlier, not much research has been undertaken that deals with the durability of markers. The researcher will review current practices on the laboratory testing procedures for RRPMs. The researcher will study the basic concepts and applications of finite element analysis. In addition, the researcher will review literature dealing with contact of vehicle tires over small obstructions.

Task 2: Study Design
As a part of this task, the researcher will gather preliminary information required to initiate the modeling and simulation of tire-marker impacts. The most important part of this task is to obtain the constitutive chemical composition and material properties of markers like tensile strength, compressive strength, modulus of elasticity, modulus of rigidity etc. for different components of markers. The researcher intended to perform laboratory tests to get the chemical composition and material properties of the markers. However, he found that such laboratory testing is infeasible or impractical. Hence, the researcher will rely on information from RRPM manufacturers or literary sources for the material properties. The researcher will also assume external loading conditions like vehicle weight, axle weight, vehicle velocity, etc. based on the general conditions. The researcher will assume pavement as a rigid surface and RRPM bonded rigidly to it.

The following inputs will be defined for the model:

- Components of the tire-marker model,
- Geometry of the tire-marker model,
• Material and section properties of the tire-marker model,
• Loading conditions,
• boundary conditions of the contacts, and
• Initial conditions like velocity, impact angle and impact location.

**Task 3: Finite Element Modeling**
As a part of this task, the researcher will model the tire-marker impacts in Hypermesh. The preliminary model for tire-marker impacts is already in place (Figure 2). The marker body in the preliminary model does not have any constitutive material properties. Hence, it acts as a rigid object. The researcher will include the constitutive composition and material properties obtained in the previous task in to the upgraded model.

This study aims at modeling one to three markers. The first step in this task is to make geometric models of the markers. The next step is the finite element meshing of the geometric models. The number of finite elements required for meshing is selected by engineering judgment. Once the finite element modeling of markers is done, tire-marker impact simulation can be run on LS-DYNA.

![Figure 2. Preliminary Finite Element Model of Tire-Marker Impacts](image)

**Task 4: Model Calibration**
The next important step is to calibrate the model. The researcher will design an experimental setup for this task. The initial idea for calibration was to measure the strains at various locations on/inside markers during the tire-marker impacts using strain gauges. However, from discussions with experts, the researcher found that estimation of strains using strain gauges in real tire-
marker impacts was quite impractical. The impact of tire over marker could break the sensitive strain gauges. In addition, there were many external factors in the field conditions which could not be controlled and thus would have affected the calibration process. Instead, the researcher will calibrate the model in the laboratory. It is a more practical and controlled way of calibrating the model. This way the researcher can focus on calibrating intrinsic properties of markers while controlling external variables.

As a part of this calibration, the researcher will design a laboratory experimental setup, which will be similar to the ASTM longitudinal flexural test for testing the markers (2). In addition, he will make a finite element model of the laboratory setup. He will get estimates of the strains in the laboratory conditions by putting strain gauges on markers. This will help to calibrate the tire-marker impact finite element model, which in turn will help in getting true estimates of material properties.

The researcher will analyze the results of the computer simulation with the same set-up as in experimental conditions. Based on this analysis, the researcher will do the post-processing of the model to calibrate it. The software Hyperview can be used for this purpose. The researcher will refine the model and repeat the analysis, if needed. The only control variable during the calibration process would be material properties. The researcher will vary the material properties so that the results of the computer simulation are in a reasonable range of the results of laboratory test. Once the model is calibrated, it will be ready for simulation of real conditions.

Task 5: Simulation of Real World Conditions
After the calibration is done, the model can be simulated in LS-DYNA to get the estimates of critical magnitudes and locations inside markers in real world conditions. The researcher will perform simulations with different marker models and external factors like loadings, tire velocities, angles of impact and impact locations.

Task 6: Analysis
The simulation will provide the magnitudes and locations of the critical stresses inside a marker when the vehicle tire runs over it. These stress profiles under different conditions (tire speeds, loadings, impact angles and impact locations) will be documented and analyzed. This analysis
will not be sufficient for finding a laboratory test that can produce the same kinds of stresses in the markers as during real tire-marker impacts. To accomplish that, different loading conditions should be simulated over markers. The simulation, which would produce the similar stress profiles in markers as produced during tire-marker impact simulation, will give the insight into the laboratory test required for RRPMs.

The next step in the analysis is to simulate a few loading conditions on markers. This is similar to simulating the ASTM longitudinal flexural test in computer as would be done for the calibration. However, no actual laboratory test is required for this part of research. The researcher will analyze the stress profiles inside the markers from simulating these loading conditions and compare them with those produced during the tire-marker impact simulations. This analysis will provide an insight in the appropriate testing conditions needed for RRPMs, which is the primary objective of the thesis. If one of the simulated loading conditions produced the stresses that were similar to those produced by tire-marker impact simulation, then the researcher will recommend a laboratory test based on the simulated loading condition. However, if none of the simulated loading conditions produced the stresses produced during tire-marker impact simulation, then the researcher will recommend simulating more loading conditions for future studies.

**Task 7: Conclusions and Recommendations**

The researcher will conclude with a concise documentation of the research methodology, analysis and results. He will recommend the testing procedures, which could simulate the field conditions of tire-marker impacts in the in-house facilities, based on the information from the finite element analysis and simulation. For example, if it was considered that the critical stresses in the markers during tire-marker impacts could be produced by performing a longitudinal flexural test (2), then that test will be recommended. Other kinds of tests like a compression test or impact test can be recommended based on their applicability. If no test was considered suitable for generating similar stresses to those during simulated tire-marker impacts, then researcher will recommend simulating more loading conditions. In addition, the researcher will list the limitations of the study and make recommendations for future studies.
REFERENCES


