WORK ORDER 7: Portable Sign Crash Test

NUMERICAL MODELING INTERIM REPORT

Submitted To:

The Pennsylvania Department of Transportation

February 2007

Pennsylvania Transportation Institute

The Pennsylvania State University
201 Transportation Research Bldg.
University Park, PA 16802
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Submitted To:

The Pennsylvania Department of Transportation

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1 Introduction

1.1 Problem Statement

Current portable sign post structures being used by PennDOT, supporting signs less than 36” x 36” square at heights of 7’ off the ground, are assembled using varying of techniques and materials and currently do not meet crash testing standards established in NCHRP 350[1]. This project is being performed to meet the NCHRP 350[1] criteria and establish a standard PennDOT support design protocol.

1.2 Objectives

The objectives of this project are to: (1) search available literature to establish the state-of-the-art for portable sign-post structures in the U.S. for further study; (2) perform numerical modeling of selected sign posts designs to present optimal designs for crash testing according to NCHRP 350[1]; (3) develop a crash testing plan for sign posts recommended by PennDOT and have the plan approved by relevant PennDOT personnel and (4) perform crash tests of selected sign post designs, report on the findings of the crash tests and develop standard drawings.

1.3 Scope

The following scope was developed for this project:

Task 1: Investigate State-of-the-Art for Portable Sign Structure Design in the U.S. Current literature will be examined to establish what portable sign post structures are being used by PennDOT and what sign post structures have been successfully tested following NCHRP 350[1] criteria by other government entities in the U.S. The literature search will incorporate commercially available sign support structures designs and their crash worthiness results if available. At the completion of the literature search, an interim report summarizing the findings will be submitted to PennDOT. A meeting describing the findings will follow and PennDOT will choose no more than 5 sign post designs for further study.

Task 2: Perform Numerical Modeling. After PennDOT has selected no more than five sign post designs for further study, models of the selected designs will be developed in LS-DYNA. The models will be developed by taking advantage of the inherent optimization feature of LS-DYNA to ensure that modifications for the improvement of the analyzed structures can be performed efficiently. The structures will be crash tested numerically; the virtual crash test simulation will be prepared to replicate the conditions of the full scale crash testing scenario of the NCHRP 350[1] test levels 3-60 and 3-61 for support structures. The simulation results will be evaluated according to NCHRP 350[1] Section 3.2.3.2, evaluation standard for breakaway utility poles. The performance of these designs will be examined and compared. The finding will be presented in an interim report. A meeting describing the findings will follow and PennDOT will choose no more than two sign post designs for further study.
Task 3: **Develop Crash Test Plans and Conduct Crash Test.** After PennDOT has selected no more than two sign post designs for further study, crash testing plans will be developed and submitted to relevant PennDOT personnel for approval. Two tests are recommended for the selected support structures using the recommended 820C vehicle: a low-speed test at 35km/h and a high-speed test at 100km/h. The low speed test is generally intended to evaluate the breakaway, fracture, or yielding mechanism of the support whereas the high speed test is intended to evaluate vehicle and test article trajectory. Occupant risk is of concern in both tests. If the primary concern regarding the impact behavior of the selected support systems based upon the simulation results is penetration of the test article or parts thereof into the occupant compartment as opposed to occupant impact velocity, ride-down acceleration and vehicular stability, it may be preferable to use the 2000P vehicle in lieu of the 820C vehicle. The choice will depend on the front profile of the two vehicles in relation to the geometry of the selected sign post structures and footings that could potentially penetrate the occupant compartment. The obtained simulation results also will be used for the planning of the critical impact point and angle of the crash tests. If the LS-DYNA results warrant possibility then the left or right quarter point of the impact vehicle bumper will be recommended to be aligned with the vertical centerline of the support structures. NCHRP 350\(^1\) has a provision to allow the same vehicle to be used to conduct both required tests (60 and 61) provided damage to the vehicle from the first test (usually the low speed test) has no appreciable effect on impact performance of the vehicle in the second test. Once the plans have been approved, crash testing following NCHRP 350\(^1\) Section 3.2.3, “Support Structures, Work Zone Traffic Control Devices, and Breakaway Utility Poles,” guidelines will occur. Findings from the tests will be examined.

Task 4: **Prepare Final Report and Standard Drawings.** At the completion of the crash test and review of the data a final report will be developed that will recommend final designs for portable sign post structures. In addition, standard drawings of the crashed sign post designs will be prepared following PennDOT guidelines.

Task 5: **Summary of the Problem Statement and Findings.**

This report constitutes the deliverable associated with Task 2.

2 **Numerical Modeling**

The first deliverable associated with the project\(^2\) recommended the five sign structures be examined numerically. These structures were selected using a filtering approach centered around information presented in two Federal Highway Administration (FHWA) databases\(^3,4\). The structures that were recommended were as follows:

1. Easel framed structures (E) – Structure Code WZ-75
2. H-shaped base structures (H) – Structure Code WZ-129
3. Rectangular base structures (R) – Structure Code WZ-110
5. X-shaped base structures (X) – Structure Code WZ-114.
PennDOT did not select any of the recommended structures and chose five other structures using criteria that were unknown to the research team. The following five signs were those chosen by PennDOT for finite element analysis:

1. Pennsylvania structure – X-shape
2. Pennsylvania structure – H-shape
3. Minnesota structure
4. Oregon structure
5. New York structure

The selected five structures are illustrated in Appendix A through Appendix E.

Numerical crash-testing was performed using LS-DYNA for each of the five PennDOT selected structures. Each sign structure was subjected to virtual crash tests using a Geo Metro vehicle (a standard 820C vehicle according to NCHRP 350 designation) with the sign oriented facing the vehicle and at 90° with respect to the vehicle. These tests were run with the top of the sign between 63” (1600mm) and 95” (2413mm) from the ground. Detailed information related to: model construction; constitutive models; support conditions, and load application (i.e. vehicle geometry, construction and speed) is provided in the sections that follow.

2.1 Model Construction

2.1.1 Sign Structure Construction

The five selected sign structures were modeled in two groups. The first group consists of steel supported structures and aluminum sign panels. The Pennsylvania structures (X-shape and H-shape) and the Minnesota structure are included in the first group. The second group is comprised of the timber supported structures and plywood sign panels (Oregon and New York structures).

The Pennsylvania sign structures are depicted as shown in Appendix A, and B. The horizontal legs and vertical stands having 0.109” (2.77mm) thickness were modeled using shell elements provided by LS-DYNA. The aluminum sign panels consisting of a 36” (914.4mm)x36” (914.4mm) square plate with a 0.1” (2.54mm) thickness were also created using shell elements. The Minnesota sign structure design plans are illustrated in Appendix C. The steel H-support, vertical mast and sleeve with 0.109” (2.77mm) thicknesses were modeled using shell elements. The 30” (762mm)x30” (762mm) square sign panel with a 0.1” (2.54mm) thickness were modeled using shell elements. Steel stands were modeled using nominal A36 steel properties available in LS-DYNA and standard aluminum properties (i.e., 6061-T6) were used for representing the aluminum panels.

The design plans for the Oregon and New York sign structures are illustrated in Appendices D and E, respectively. The single post structure from Appendix D, consisting of the I-shaped base and 36” (914.4mm)x36” (914.4mm) plywood sign panel, was selected as the Oregon structure to be modeled. The Oregon single post was modeled using 3D solid elements to represent the timber stand, the I-shape base and the plywood sign panel, respectively. The New York sign
structure was composed of a wooden stand and 36’’ (914.4mm)x36’’ (914.4mm) plywood sign panel and it was modeled using solid elements, as well. Material models for pine available in LS-DYNA were used to represent the nominal properties for both structures.

All sign structures were constructed according to the design plans. All sign panels were modeled separately from their support structures and placed onto them using constrained rivets provided by LS-DYNA, which couple the models together. The safety light placed on top of the sign was modeled matching published dimensions and weights to represent a worst case scenario with respect to low speed crash tests. It was modeled using a hard plastic material and affixed to the top of the sign using the constrained rivets.

2.1.2 Vehicle Model Construction

A standard NCHRP approved vehicle model developed by the FHWA/NHTSA National Crash Analysis Center (NCAC) was used for the numerical crash tests. Model information is as follows:

1. Number of Parts 230
2. Number of Nodes 100348
3. Number of Solids 1209
4. Number of Springs 8
5. Number of mass elements 76
6. Number of Elements 16000

The vehicle model can be observed in Figure 1.

![Figure 1. Detailed vehicle model (http://www.ncac.gwu.edu/vml/models.html)](http://www.ncac.gwu.edu/vml/models.html)
2.1.3 Crash Scenario Modeling

The crash scenarios were selected after consulting with an official from FHWA familiar (Conversation, N. Artimovich, FHWA Office of Safety Design, DATE) with NCHRP 350\textsuperscript{[1]} Section 3.2.3, “Support Structures, Work Zone Traffic Control Devices, and Breakaway Utility Poles”. Using a test matrix from the guide it was decided in cooperation with the FHWA official to employ Level 3 test requirements of the “support Structures” category with test levels 3-60 and 3-61.

These tests include a low speed crash scenario as well as a high speed crash scenario as listed below:

Test Level 3-60. The test comprised two separate full crash scenarios at 35 km/h (22 mph) with the 820C vehicle (Geo Metro) using sign impact angles of 0 and 90 degrees as described above. Each portable sign structure crash scenario was analyzed twice. The first analysis was performed with the sign structure facing the approaching vehicle and impacting its front either at the vehicle’s geometric middle or at one of the quarter points with respect to its longitudinal centerline according to NCHRP 350 requirements. The second analysis had the sign structure rotated 90 degrees from its initial position and placed at the middle point of the approaching vehicle.

Test Level 3-61. The test comprised two separate full crash scenarios at 100 km/h (62 mph) with the 820C vehicle (Geo Metro) using sign impact angles of 0 and 90 degrees as described above. Each portable sign structure crash scenario was analyzed twice. The first analysis was performed with the sign structure facing the approaching vehicle and impacting its front either at the vehicle’s geometric middle or at one of the quarter points with respect to its longitudinal centerline. The second analysis had the sign structure rotated 90 degrees from its initial position and placed at the middle or at the other quarter point of the approaching vehicle.

The virtual crash scenarios were developed following these conditions. The model was created so that each support structure was placed at the geometric longitudinal middle of the approaching vehicle to represent the critical scenario for each individual crash test. The structures were placed a short distance from the original location of the vehicle to ensure that the vehicle was in a dynamically stable condition with a constant direction and speed free from dynamic effects before impact. The structure was placed on an infinitely rigid smooth surface representing the ground and was given a nominal coefficient of friction of 0.3 at contact locations with the ground. The portion of the structure in contact was then loaded with a model representing four sand bags on the end of each support leg. The incorporation of the sand bags represented real life conditions.

Prior to the numerical crash test the vehicle was initialized to the following conditions:

- Initial speed of all components was set to the desired nominal test speed.
- Rotational speed of the tires was set to matching angular velocities to avoid differential
frictional and inertial effects from the moving vehicle.

- The vehicle, at its defined initial speed and tires angular velocities, was placed on a perfectly smooth and level infinitely rigid surface with a friction coefficient of 0.3.

3 Modeling Results and Recommendations

3.1 Analysis

To ensure compatibility of results obtained from the FEA simulation to the full scale crash tests comparable statistics and metrics needed to be developed that were related to NCHRP 350[1] requirements. Parameters required by NCHRP 350[1] to be measured and analyzed and to meet certain requirements were identified and tracked in the virtual crash simulation. To produce these necessary parameters numerically the procedures outlined below was followed.

In the finite element model a virtual accelerometer was placed at the vehicle CG. The virtual accelerometer was configured so that all accelerations of the element to which it was assigned were recorded in a local coordinate system, defined by the placement and orientation of the accelerometer, rather than recording these items in a global coordinate system as followed for all other model output. This replicates performance of the accelerometer used during full scale crash testing. If the accelerometer can not be placed at the exact CG for the full scale test, which is typically the case, the distance from the CG to the accelerometer will be recorded accelerations corrected accordingly.

To evaluate virtual crash test data using the accelerometer the following tasks were completed:

- Recording time spans for all reported data were generally produced from impact until the simulation ended however, in certain cases; simulations were produced until 0.05s after impact.
- Accelerations in all three directions (a_x, a_y, a_z) of the accelerometer as function of time were measured, with measurements being produced at the same time step as the simulation run.
- Displacements (S_x, S_y) at select locations were found by double integrating acceleration data (a_x, a_y):

\[
S_x(t) = \int_{t_1} a_x dt
\]

\[
S_y(t) = \int_{t_1} a_y dt
\]

- The times when S_x(t_1)=0.6m and S_y(t_2)=0.3m were calculated and recorded. These t_1 and t_2 times represented the instances when a crash dummy head would come into contact with the steering wheel/dashboard and the side door, respectively. However, for all analyses the portable sign structures did not provide enough obstruction and therefore within the allotted time frame these displacements did not occur. For information the, S_x and S_y distance values reached by at the end of the simulations are reported in the data analysis.
Recorded accelerations \((a_x, a_y, a_z)\) were further reduced as follows:

- Output values were filtered using a low pass filter with 10ms cutoff frequency;
- Filtered accelerations were used to calculate speeds:

\[
V_i^{x,y}(t) = \int_0^t \sqrt{a_x^2 + a_y^2} \, dt
\]  
(3.3)

\[
V_i^{x,y}(t) = \int_0^t \sqrt{a_x^2 + a_y^2} \, dt
\]  
(3.4)

\[
V_i^z(t) = \int_0^t a_z \, dt
\]  
(3.5)

- Accelerations corresponding to times \(t_1\) and \(t_2\) as discussed above were recorded as \(a_x(t_1)\) and \(a_y(t_2)\).

These procedures were performed for all 10 analysis cases: 5 portable sign structures facing the vehicle and 5 structures rotated 90 degrees with respect to the vehicle’s longitudinal centerline. These scenarios were simulated at the 35km/h and the 100km/h speeds.

Additional evaluations of deformations and penetrations involved tracking the following data for each case:

- The node and element of the car with the highest permanent deformation.
- A representative node and element on the car that sustained no deformation.
- Generating a trace of each of the previously selected nodes with respect to time.
- Calculating relative distances between the previously selected nodal traces using their recorded data and relative distance between them:

\[
D_{Def}(t) = \sqrt{(x(t_1) - x(t_2))^2 + (y(t_1) - y(t_2))^2 + (z(t_1) - z(t_2))^2}
\]  
(3.6)

- Monitoring collision of the sign structure with different parts of the vehicle model and recording the node and element of the structure that penetrated the vehicle (if penetration occurred).
- Monitoring an adjacent node and element on the vehicle closest to the structure penetration location.
- Generating a trace of each of the previously selected nodes with respect to time.
- Calculating relative distances between the previously selected nodal traces using their recorded data and relative distance between them:

\[
D_{Pen}(t) = \sqrt{(x(t_1) - x(t_2))^2 + (y(t_1) - y(t_2))^2 + (z(t_1) - z(t_2))^2}
\]  
(3.7)

- Recording the maximum absolute value of the relative distance for each analysis case:

\[\text{Max}\{D_{Def}(t)\} \quad \text{and} \quad \text{Max}\{D_{Pen}(t)\}\]
The data was collected and reported in the format shown in Table 1.

Table 1. NCHRP parameters from simulation

| Structure name | Position | Vehicle speed | t1 | t2 | \( V_{t1} \) | \( V_{t2} \) | \( a_{x}(t_1) \) | \( a_{y}(t_2) \) | Max\( |D_{x,y}(t)| \) |
|----------------|---------|---------------|----|----|-------------|-------------|----------------|----------------|----------------|
| Minnesota      | 0 degree | 100km/h       |    |    |             |             |                |                |                |
| Minnesota      | 90 degree| 100km/h       |    |    |             |             |                |                |                |
| Minnesota      | 0 degree | 35km/h        |    |    |             |             |                |                |                |
| Minnesota      | 90 degree| 35km/h        |    |    |             |             |                |                |                |

The data in the Table 1 will provide a solid quantitative foundation based on the NCHRP 350 crash evaluation criteria to compare the performance of the different sign structures. The calculated performance parameters will be compared to the NCHRP guidelines and will be compared within the group of structures to aid the selection of a design for full scale crash test. The different parameters will be balanced in an evaluation metric so that a structure with the highest likelihood to pass full scale crash testing will be selected for further tests.
3.2 Results

This section contains representative results from the analyses. Filtered results from the LS-DYNA finite element models for each of the structures are shown that depict vehicle speeds and accelerations as a function of time throughout the crash test. These figures are augmented with illustrations of the crash tests from LS-DYNA and summary tables similar to that presented in the previous section.

For each structure, results are shown for the critical speed and sign height (35km/hr, sign a lower height). They are shown for two sign orientations relative to the vehicle: 0 degrees (sign facing vehicle) and 90 degrees (sign perpendicular to vehicle).

3.2.1 Pennsylvania structure – X-shape

3.2.1.1 35km/h with 0deg orientation

Measured speeds and decelerations are presented in the following figures.
Figure 2. Speed and deceleration for 35km/hr with 0deg orientation

(a) at the point of impact  (b) 0.035s after impact

(c) 0.05s after impact  (d) 0.1s after impact

Figure 3. Right view of crashing simulation
(a) at the point of impact  
(b) 0.035s after impact  
(c) 0.05s after impact  
(d) 0.1s after impact  

Figure 4. ISO view of crashing simulation
3.2.1.2 35km/h with 90deg orientation

Measured speeds and decelerations are presented in the following figures.

Figure 5. Speed and deceleration for 35km/hr with 90deg orientation
Figure 6. Right view of crashing simulation

Figure 7. ISO view of crashing simulation
Results for the Pennsylvania X-shape structure are summarized in the following table.

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>t1(sec)</th>
<th>t2(sec)</th>
<th>V1x(t1), m/sec</th>
<th>V1y(t1), m/sec</th>
<th>Sx, m</th>
<th>Sy, m</th>
<th>ax(t1), m/s²</th>
<th>ay(t2), m/s²</th>
<th>Ddef(t) mm</th>
<th>Dpen(t) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn X-shape</td>
<td>0 degree</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.200</td>
<td>0.375</td>
<td>0.152</td>
<td>0.018</td>
<td>-94.782</td>
<td>26.601</td>
<td>355.193</td>
<td>77.200</td>
</tr>
<tr>
<td>Penn X-shape</td>
<td>90 degree</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.432</td>
<td>0.132</td>
<td>0.165</td>
<td>0.007</td>
<td>-82.691</td>
<td>18.613</td>
<td>357.737</td>
<td>136.000</td>
</tr>
<tr>
<td>Penn X-shape</td>
<td>0 degree</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>1.410</td>
<td>0.120</td>
<td>0.090</td>
<td>0.010</td>
<td>-16.310</td>
<td>-4.440</td>
<td>69.783</td>
<td>0.000</td>
</tr>
<tr>
<td>Penn X-shape</td>
<td>90 degree</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>1.881</td>
<td>0.166</td>
<td>0.091</td>
<td>0.010</td>
<td>-32.043</td>
<td>-7.803</td>
<td>162.396</td>
<td>10.000</td>
</tr>
</tbody>
</table>
3.2.2 Pennsylvania structure – H-shape

3.2.2.1 35km/h with 0deg orientation

Measured speeds and decelerations are presented in the following figures.

(a) Measured vehicle speed vs. time

(b) Measured vehicle acceleration vs. time

Figure 8. Speed and deceleration for 35km/hr with 0deg orientation
Figure 9. Right view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact
(c) 0.05s after impact     (d) 0.1s after impact

Figure 10. ISO view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact
(c) 0.05s after impact     (d) 0.1s after impact
3.2.2.2 35km/h with 90deg orientation

Measured speeds and decelerations are presented in the following figures.

(a) Measured vehicle speed vs. time

(b) Measured vehicle acceleration vs. time

Figure 11. Speed and deceleration for 35km/hr with 90deg orientation
(a) at the point of impact     (b) 0.035s after impact

(c) 0.05s after impact      (d) 0.1s after impact

Figure 12. Right view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact

(c) 0.05s after impact      (d) 0.1s after impact

Figure 13. ISO view of crashing simulation
Results for the Pennsylvania H-shape structure are summarized in the following table.

**Table 3. Simulation results from Pennsylvania (Penn) H-shape**

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>t1(sec)</th>
<th>t2(sec)</th>
<th>V1x(t1), m/sec</th>
<th>V1y(t1), m/sec</th>
<th>Sx, m</th>
<th>Sy, m</th>
<th>ax(t1), m/s²</th>
<th>ay(t2), m/s²</th>
<th>Ddef(t) mm</th>
<th>Dpen(t) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn H-shape</td>
<td>0°</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.870</td>
<td>0.165</td>
<td>0.168</td>
<td>0.007</td>
<td>-122.648</td>
<td>12.420</td>
<td>354.381</td>
<td>90.840</td>
</tr>
<tr>
<td>Penn H-shape</td>
<td>90°</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.979</td>
<td>0.715</td>
<td>0.171</td>
<td>0.028</td>
<td>-119.036</td>
<td>35.034</td>
<td>373.545</td>
<td>110.500</td>
</tr>
<tr>
<td>Penn H-shape</td>
<td>0°</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>2.099</td>
<td>0.091</td>
<td>0.090</td>
<td>0.009</td>
<td>-58.616</td>
<td>-13.513</td>
<td>86.341</td>
<td>0.000</td>
</tr>
<tr>
<td>Penn H-shape</td>
<td>90°</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>2.123</td>
<td>0.111</td>
<td>0.112</td>
<td>0.008</td>
<td>-34.340</td>
<td>-11.611</td>
<td>205.830</td>
<td>12.868</td>
</tr>
</tbody>
</table>
3.2.3 Minnesota structure

3.2.3.1 35km/h with 0deg orientation

Measured speeds and decelerations are presented in the following figures.

Figure 14. Speed and deceleration for 35km/hr with 0deg orientation
Figure 15. Right view of crashing simulation

(a) at the point of impact    (b) 0.035s after impact
(c) 0.05s after impact    (d) 0.1s after impact

Figure 16. ISO view of crashing simulation

(a) at the point of impact    (b) 0.035s after impact
(c) 0.05s after impact    (d) 0.1s after impact
3.2.3.2 Minnesota sign post (35km/h with 90deg orientation)

Measured speeds and decelerations are presented in the following figures.

(a) Measured vehicle speed vs. time

(b) Measured vehicle acceleration vs. time

Figure 17. Speed and deceleration for 35km/hr with 90deg orientation
Figure 18. Right view of crashing simulation

(a) at the point of impact
(b) 0.035s after impact
(c) 0.05s after impact
(d) 0.1s after impact

Figure 19. ISO view of crashing simulation

(a) at the point of impact
(b) 0.035s after impact
(c) 0.05s after impact
(d) 0.1s after impact
Results for the Minnesota structure are summarized in the following table.

**Table 4. Simulation results from Minnesota structure**

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>t1 (sec)</th>
<th>t2 (sec)</th>
<th>Vx(t1), m/sec</th>
<th>Vy(t1), m/sec</th>
<th>Sx, m</th>
<th>Sy, m</th>
<th>ax(t1), m/s²</th>
<th>ay(t2), m/s²</th>
<th>Ddef(t) mm</th>
<th>Dpen(t) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minnesota</td>
<td>0°</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>5.076</td>
<td>0.423</td>
<td>0.159</td>
<td>0.022</td>
<td>-113.277</td>
<td>16.888</td>
<td>386.360</td>
<td>101.560</td>
</tr>
<tr>
<td>Minnesota</td>
<td>90°</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>3.372</td>
<td>0.550</td>
<td>0.092</td>
<td>0.024</td>
<td>-81.565</td>
<td>11.001</td>
<td>473.048</td>
<td>12.600</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0°</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>1.920</td>
<td>0.066</td>
<td>0.102</td>
<td>0.005</td>
<td>-51.678</td>
<td>-12.757</td>
<td>98.185</td>
<td>0.000</td>
</tr>
<tr>
<td>Minnesota</td>
<td>90°</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>2.060</td>
<td>0.398</td>
<td>0.073</td>
<td>0.010</td>
<td>-43.780</td>
<td>10.306</td>
<td>279.321</td>
<td>10.000</td>
</tr>
</tbody>
</table>
3.2.4 Oregon structure

3.2.4.1 35km/h with 0deg orientation

Measured speeds and decelerations are presented in the following figures.

Figure 20. Speed and deceleration for 35km/hr with 0deg orientation
(a) at the point of impact     (b) 0.035s after impact

(c) 0.05s after impact     (d) 0.1s after impact

**Figure 21.** Right view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact

(c) 0.05s after impact     (d) 0.1s after impact

**Figure 22.** ISO view of crashing simulation
3.2.4.2 35km/h with 90deg orientation

Measured speeds and decelerations are presented in the following figures.

(a) Measured vehicle speed vs. time

(b) Measured vehicle acceleration vs. time

Figure 23. Speed and deceleration for 35km/hr with 90deg orientation
Figure 24. Right view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact
(c) 0.05s after impact     (d) 0.1s after impact

Figure 25. ISO view of crashing simulation

(a) at the point of impact     (b) 0.035s after impact
(c) 0.05s after impact     (d) 0.1s after impact
Results for the Oregon structure are summarized in the following table.

Table 5. Simulation results from Oregon structure

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>t1(sec)</th>
<th>t2(sec)</th>
<th>V1x(t1), m/sec</th>
<th>V1y(t1), m/sec</th>
<th>Sx, m</th>
<th>Sy, m</th>
<th>ax(t1), m/s²</th>
<th>ay(t2), m/s²</th>
<th>Ddef(t), mm</th>
<th>Dpen(t), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>0º</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.194</td>
<td>0.667</td>
<td>0.100</td>
<td>0.024</td>
<td>-</td>
<td>-</td>
<td>101.352</td>
<td>46.592</td>
</tr>
<tr>
<td>Oregon</td>
<td>90º</td>
<td>100km/h</td>
<td>(n/a 0.110)</td>
<td>(n/a 0.110)</td>
<td>4.233</td>
<td>0.256</td>
<td>0.173</td>
<td>0.016</td>
<td>-65.268</td>
<td>15.572</td>
<td>105.700</td>
<td>0.000</td>
</tr>
<tr>
<td>Oregon</td>
<td>0º</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>1.233</td>
<td>0.130</td>
<td>0.107</td>
<td>0.010</td>
<td>-35.711</td>
<td>8.867</td>
<td>43.200</td>
<td>0.000</td>
</tr>
<tr>
<td>Oregon</td>
<td>90º</td>
<td>35km/h</td>
<td>(n/a 0.148)</td>
<td>(n/a 0.148)</td>
<td>2.067</td>
<td>0.258</td>
<td>0.210</td>
<td>0.015</td>
<td>-44.321</td>
<td>26.029</td>
<td>41.800</td>
<td>0.000</td>
</tr>
</tbody>
</table>
3.2.5 New York structure

3.2.5.1 35km/h with 0deg orientation

Measured speeds and decelerations are presented in the following figures.

Figure 26. Speed and deceleration for 35km/hr with 0deg orientation
Figure 27. View of crashing simulation (i.e., Right and ISO view)
3.2.5.2 35km/h with 90deg orientation

Measured speeds and decelerations are presented in the following figures.

(a) Measured vehicle speed vs. time

(b) Measured vehicle acceleration vs. time

Figure 28. Speed and deceleration for 35km/hr with 90deg orientation
(a) at the point of impact

(b) 0.035s after impact

(c) 0.05s after impact

Figure 29. View of crashing simulation (i.e., Right and ISO view)

Results for the New York structure are summarized in the following table.

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>t1(sec)</th>
<th>t2(sec)</th>
<th>$V_{x1}(t1)$, m/sec</th>
<th>$V_{y1}(t1)$, m/sec</th>
<th>$S_x$, m</th>
<th>$S_y$, m</th>
<th>$a_{x1}(t1)$, m/s$^2$</th>
<th>$a_{y1}(t2)$, m/s$^2$</th>
<th>Ddef(t), mm</th>
<th>Dpen(t), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>0°</td>
<td>100km/h</td>
<td>n/a</td>
<td>0.110</td>
<td>6.132</td>
<td>0.744</td>
<td>0.246</td>
<td>0.020</td>
<td>-110.451</td>
<td>21.556</td>
<td>191.696</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>90°</td>
<td>100km/h</td>
<td>n/a</td>
<td>0.110</td>
<td>0.897</td>
<td>0.184</td>
<td>0.046</td>
<td>0.015</td>
<td>-13.526</td>
<td>7.342</td>
<td>69.900</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>0°</td>
<td>35km/h</td>
<td>n/a</td>
<td>0.148</td>
<td>1.022</td>
<td>0.111</td>
<td>0.126</td>
<td>0.007</td>
<td>-43.410</td>
<td>-6.136</td>
<td>10.700</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>90°</td>
<td>35km/h</td>
<td>n/a</td>
<td>0.148</td>
<td>0.149</td>
<td>0.897</td>
<td>0.015</td>
<td>0.007</td>
<td>4.747</td>
<td>-12.387</td>
<td>6.300</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 6. Simulation results from New York structure
Table 7 summarizes results obtained from the considered sign structure simulations.

### Table 7. Table of performance parameters from simulation results

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>( \tau ) (sec)</th>
<th>( \phi ) (deg)</th>
<th>( V_{x1}(\text{m/sec}) )</th>
<th>( V_{y1}(\text{m/sec}) )</th>
<th>( V_{z1}(\text{m/sec}) )</th>
<th>( \rho ) (m)</th>
<th>( \omega ) (deg/\text{sec}²)</th>
<th>( \omega ) (deg/\text{sec}²)</th>
<th>( \delta_{1}(\text{deg}) )</th>
<th>( \delta_{2}(\text{deg}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>4.230</td>
<td>3.775</td>
<td>0.192</td>
<td>0.018</td>
<td>94.782</td>
<td>25.601</td>
<td>355.193</td>
<td>77.200</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>4.432</td>
<td>3.122</td>
<td>0.165</td>
<td>0.007</td>
<td>82.891</td>
<td>18.613</td>
<td>277.737</td>
<td>150.600</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>1.410</td>
<td>0.120</td>
<td>0.990</td>
<td>0.010</td>
<td>10.316</td>
<td>-4.443</td>
<td>69.762</td>
<td>0.000</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>1.591</td>
<td>0.106</td>
<td>0.001</td>
<td>0.010</td>
<td>32.043</td>
<td>-7.903</td>
<td>162.206</td>
<td>10.600</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>6.070</td>
<td>0.145</td>
<td>0.000</td>
<td>0.000</td>
<td>122.918</td>
<td>30.426</td>
<td>204.201</td>
<td>190.649</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>4.979</td>
<td>0.115</td>
<td>0.171</td>
<td>0.025</td>
<td>-118.936</td>
<td>36.034</td>
<td>373.545</td>
<td>110.600</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>2.099</td>
<td>0.090</td>
<td>0.000</td>
<td>0.000</td>
<td>-58.016</td>
<td>-13.513</td>
<td>60.341</td>
<td>0.000</td>
</tr>
<tr>
<td>Penn % shape</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>2.123</td>
<td>0.111</td>
<td>0.112</td>
<td>0.008</td>
<td>-34.346</td>
<td>-11.611</td>
<td>205.930</td>
<td>12.666</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>5.076</td>
<td>4.223</td>
<td>1.159</td>
<td>0.022</td>
<td>-113.277</td>
<td>16.888</td>
<td>386.360</td>
<td>101.560</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>3.372</td>
<td>3.550</td>
<td>0.992</td>
<td>0.022</td>
<td>-81.665</td>
<td>11.001</td>
<td>243.048</td>
<td>12.600</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>0.572</td>
<td>0.598</td>
<td>0.073</td>
<td>0.010</td>
<td>-43.786</td>
<td>10.308</td>
<td>279.791</td>
<td>10.600</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>0.194</td>
<td>0.667</td>
<td>0.190</td>
<td>0.024</td>
<td>-191.362</td>
<td>40.592</td>
<td>127.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Oregon</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>0.208</td>
<td>0.208</td>
<td>0.000</td>
<td>0.000</td>
<td>-58.266</td>
<td>15.572</td>
<td>105.700</td>
<td>0.000</td>
</tr>
<tr>
<td>Oregon</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>1.233</td>
<td>1.233</td>
<td>0.000</td>
<td>0.000</td>
<td>-55.711</td>
<td>6.887</td>
<td>43.200</td>
<td>0.000</td>
</tr>
<tr>
<td>Oregon</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>2.087</td>
<td>2.087</td>
<td>0.000</td>
<td>0.000</td>
<td>-44.321</td>
<td>-26.029</td>
<td>8.030</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>6.013</td>
<td>7.444</td>
<td>1.256</td>
<td>0.056</td>
<td>-118.451</td>
<td>24.556</td>
<td>191.606</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>0 degree</td>
<td>165 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>6.037</td>
<td>6.164</td>
<td>0.846</td>
<td>0.015</td>
<td>-13.326</td>
<td>7.342</td>
<td>66.000</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>0.094</td>
<td>0.111</td>
<td>0.126</td>
<td>0.000</td>
<td>-44.614</td>
<td>-6.163</td>
<td>18.700</td>
<td>0.000</td>
</tr>
<tr>
<td>New York</td>
<td>0 degree</td>
<td>35 km/h</td>
<td>0.110</td>
<td>0.110</td>
<td>0.148</td>
<td>0.897</td>
<td>0.915</td>
<td>0.007</td>
<td>4.747</td>
<td>-12.387</td>
<td>6.300</td>
<td>0.000</td>
</tr>
</tbody>
</table>

In the evaluation of the design structures the “Flail-Space Model” from NCHRP is used. In this analysis we have adopted the simplified point mass, flail-space model for assessing risks to occupants within the impacting vehicle due to vehicular accelerations according to the allowed NCHRP procedures. Two measures of risk are used; (1) the velocity at which a hypothetical occupant impacts a hypothetical interior surface and (2) "ridedown" acceleration subsequently experienced by the occupant. Assumptions made in the current model were:

(a) Occupant positioned at the vehicle's center of mass;
(b) Yaw motions of vehicle are ignored and, consequently, motion of the occupant in the lateral direction is completely independent of motion in the longitudinal direction,
(c) Vehicular and occupant motion is planar (in x-y plane); and
(d) Occupant contained in a compartment such that ± 0.3 m lateral movement can occur before impact with the sides of the compartment (idealized vehicular side structure), and 0.6 m longitudinal (forward) movement can occur before impact with the front of the compartment (idealized instrument panel/dash/windshield).

The calculation algorithms for these parameters are given in Section “3.1 Analysis”. In the simulated tests of the sign structures the impulse on the vehicle on almost all of the cases was relatively small and of short duration. It all of the tests the displacements \((S_x, S_y)\) (see 3.1 Analysis) was less than 0.6 m and 0.3 m, respectively, during the period in which accelerations were recorded. In such cases it is recommended that the occupant impact velocity be set equal to the vehicle's change in velocity that occurs during contact with the test article, or parts thereof. The \(V_{x1}\) and \(V_{y1}\) occupant impact velocities in Table 7 are calculated according to these NCHRP guidelines.
For the ridedown acceleration to produce occupant injury, it should have at least a minimum duration ranging from 0.007 to 0.04 sec, depending on the body component. Thus, vehicular acceleration "spikes" of duration less than 0.007s are not critical and should be averaged from the pulse. An arbitrary duration of 0.010s has been selected by NCHRP 350 as a convenient and somewhat conservative time base for averaging accelerations for occupant risk assessment. This is accomplished by taking a moving 10-ms average of vehicular "instantaneous" accelerations in the x and y directions, subsequent to the calculated occupant impact time.

The acceptable and preferred limitations contained in NCHRP 350 pertaining to portable sign structure crash testing test is given in Table 8

<table>
<thead>
<tr>
<th></th>
<th>Preferred</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant Impact velocity Limits [m/s]</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Occupant Ridedown Acceleration Limits [G's]</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

From Table 7 the aggregate occupant risk factors (the occupant impact velocity and occupant ridedown acceleration) in terms of the NCHRP criteria were calculated. In order to minimize the work necessary to compare the results and to be conservative aggregate risk factors were calculated. The aggregate factors were calculated using the following geometrical vector addition formula:

$$ Aggregate\ value = \sqrt{x^2 + y^2} $$ (4.1)

The computed aggregate occupant risk factors are given in

Table 9. The aggregate occupant impact velocities and the highest 10-ms average of the aggregate acceleration values are compared to the recommended limits in Table 8; it is desirable that both values are below the "preferable" limits; values in excess of the "maximum" limits are considered to be unacceptable.

As it can be observed from the data most of the sign structures have delivered results that are within the NCHRP given maximum limitations. The only exception is the New York sign structure that gave an occupant impact velocity that was larger than the acceptable limit. All sign post designs have occupant ridedown accelerations that are much smaller than the given upper limitation and most of them are also smaller than the preferred value. The only structure that yielded accelerations that are slightly larger than the preferred value is the Pennsylvania – H-shape signpost structure.
A ranking between the structures with regard to the total occupant risk can be established by calculating the average occupant impact velocities and occupant ridedown accelerations for each signpost design. The ranking is based upon the combined averages of the two risk factors (occupant impact velocities and occupant ridedown accelerations). Based upon this procedure the ranking for the signposts is as follows, with number 1 being the safest and number 5 being the least safe:

1. Pennsylvania – X-shape
2. Pennsylvania – H-shape
3. Minnesota
4. Oregon
5. New York

Based upon the analysis of the results it is recommended that the Pennsylvania – X-shape signpost design be selected for further analysis and testing.

### Table 9. Aggregate Occupant Risk Factors

<table>
<thead>
<tr>
<th>Sign post name</th>
<th>Position</th>
<th>Vehicle speed</th>
<th>Aggregate Occupant Impact Velocity [m/s]</th>
<th>Occupant Ridedown Acceleration [G's]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn X-shape</td>
<td>0 degree</td>
<td>100km/h</td>
<td>4.22</td>
<td>10.04</td>
</tr>
<tr>
<td>Penn X-shape</td>
<td>90 degree</td>
<td>100km/h</td>
<td>4.43</td>
<td>8.64</td>
</tr>
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APPENDIX A - Pennsylvania structure – X-shape

Square tube
Typical

90°

36" X 36"

1.8'

7'
APPENDIX B - Pennsylvania structure – H-shape
APPENDIX C - Minnesota structure

Parts List:
All square tube 12 gauge galvanized steel with 0.4375" holes on either 1" centers or drilled as needed.
(2) H skid, horizontal legs - 2" x 2" x 60" long,
(1) H skid, cross bar - 2" x 2" x 30" long,
(1) H skid, vertical stub - 2" x 2" x 12" long,
(1) Vertical mast - 2.25" x 2.25" x 60" long,
(1) Sleeve - 2.5" x 2.5" x 36" long,
Sign mounting hardware: 5/16" (0.3125") stainless steel or grade 5 zinc plated bolts and washers, nylon insert lock nut, and nylon washers against sign face.

NCHRP 350 COMPLIANT PORTABLE SIGN STAND FOR 30" X 30" STOP SIGN

APPROVED
7/15/05

DATE OF REV.
10 REFERENCES


3 Office of Engineering; U.S Department of Transportation (1998) HNG-14, “Crash Tested Work Zone Traffic Control Devices” *Federal Highway Administration*

4 Office of Engineering; U.S Department of Transportation (1997) HNG-14, “Identifying Acceptable Highway Safety Features” *Federal Highway Administration*