Transportation Research Part C 50 (2015) 28–36

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Simulating vehicle dynamics on both design plans and laser-scanned road geometry to guide highway design policy

Alexander Brown [a,*], Sean Brennan [b]

[a] Penn State University, 336D Reber Building, University Park, PA 16802, United States
[b] Mechanical Engineering, Penn State University, 157D Hammond Building, University Park, PA 16802, United States

ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 28 June 2014
Accepted 29 July 2014
Available online 27 August 2014

Keywords:
Model validation
Roadway construction
Mapping
Data collection
Simulation
Highway safety
Design guidance
Vehicle dynamics

ABSTRACT

Increasingly, roadway designers use simulations to analyze how roadway design choices affect vehicle dynamics and ultimately safety. When using commercial multi-body simulations for analysis of vehicle dynamics, engineers are usually able to trust that the vehicle states predicted by simulations are reasonably accurate. This is because simulation software companies spend significant research and development dollars making sure that vehicle models and numerical solvers give realistic results. However, when using vehicle dynamic simulations for the analysis of roadway designs, the road environment must be defined by the user. Researchers are often left to wonder whether the roads they simulate in software are representative of what construction crews actually built in the field. This paper compares the results of simulations using both a road's design geometry, i.e., the CAD plans, versus a three-dimensional point-cloud scan of its actual geometry. For this comparison, high-fidelity commercial vehicle simulation software (CarSim and TruckSim) was used. Research-grade sensing equipment allowed for the digitization of road geometries during highway traversals in the field to create a simulated mesh of the real highway geometry. After comparing simulation results for traversals of design geometry and measured road geometry with collected vehicle data, the road safety implications of discrepancies seen between the predicted and measured vehicle states are also discussed.

1. Introduction

The study that follows is a small portion of a large three-year effort funded by the National Cooperative Highway Research Program (NCHRP 15-39) to investigate current highway design policies for sharp horizontal curves and steep downgrades. The project looked at the current American Association of State Highway and Transportation Officials (AASHTO) highway design specifications (AASHTO, 2011), and how a range of highway geometries designed to these specifications affected the chances of single-vehicle skidding and rollover-related accidents occurring for a wide range of vehicle designs, and a range of braking, lane-change, and curve following scenarios. While a large portion of this study consisted of vehicle simulations of the above scenarios, the project also included an instrumented vehicle study to determine the suitability of five current roadways designed to AASHTO standards. Because correct representation of three-dimensional road geometry is paramount to accurate simulation of vehicle dynamics, as is clear from prior work in road profile measurement (Chemistruck

* Corresponding author.
E-mail addresses: aab5009@psu.edu (A. Brown), sbrennan@psu.edu (S. Brennan).

http://dx.doi.org/10.1016/j.trc.2014.07.009
0968-090X/

et al., 2009; Dembski et al., 2006; Detweiler and Ferris, 2010; Kern and Ferris, 2007; Stine et al., 2010), examination of these sites included both a data collection and a simulation component.

This paper summarizes the methodology used for obtaining real-world roadway geometry measurements for comparison to designed road geometry. While any driving situation could be simulated, the primary focus of this paper is to assess vehicle dynamics on real highway curve traversals during normal (non-emergency) operation. First, a set of field experiments was conducted in which the dynamic states of a full-sized SUV were collected using a defense-grade Inertial Navigation System (INS) while the test vehicle followed free-flowing highway traffic around a horizontal curve on a steep downgrade. This was repeated for 7 consecutive traversals of the road segment of interest, for 5 different measurement sites across 2 states. While collecting vehicle measurements, a high-fidelity LIght Distance And Ranging (LIDAR) sensor mounted on the vehicle recorded a three-dimensional point cloud representing the geometry of the road. This point cloud was then processed to generate a roadway mesh geometry. Then, simulations of a vehicle traversing the road defined by the LIDAR-measured geometry were performed in CarSim. The simulated vehicle was given the same longitudinal target speed profile as the test vehicle measured in the field. Finally, using the same longitudinal speed profile, a second simulation was performed on a road represented by the curve's *design* geometry, e.g. the Computer-Aided Design (CAD) geometry provided by the state DOT representing the design as it was built according to AASHTO policy. This procedure is outlined in Fig. 1.

The paper provides discussions of how the simulated geometries were prepared for use in CarSim, how the test vehicle and procedure were prepared, summarizes results for multiple roadways in the northeastern United States including discrepancies in geometries, and gives detailed results for selected sites to illustrate the simulation and data processing procedure. The analysis of the data from the three sources of data (measured, simulated on real road, simulated on road design geometry) shows good agreement between the simulation outputs generated by both CAD geometry and the collected data. Finally, the paper concludes with recommendations to others performing this type of research in future road safety studies.

2. Data collection methodology

Roadway geometry, cross-slope, and vehicle dynamic data were collected at five locations from in-vehicle sensors while the test vehicle followed free-flow vehicles through the sites. At each site, data were collected while following behind five separate passenger vehicles and two tractor semi-trailers. The goal of this vehicle shadowing process was to measure and thereby replicate a statistical picture of the normal traffic encountered at each roadway. This enabled simulations to use the measured speed profile of a vehicle traversing the road geometry in question, rather than a guessed or idealized speed profile, in evaluating the road's safety characteristics.

The test vehicle, a 2010 Dodge Durango, was chosen because of its capacity to hold the data collection equipment, and because the vehicle's inertial and kinematic parameters align well with those defined as a standard full-size SUV within CarSim. The vehicle was instrumented with a defense-grade Global Positioning System (GPS) (2 m 2-sigma position) coupled to a ring-laser-gyro Inertial Measurement Unit (IMU) that provided accurate low-drift absolute measures of position and orientation. The GPS/IMU data were collected at 100 Hz. Additionally, a roof-mounted LIght Detection And Ranging (LIDAR) was mounted on a gantry behind and above the vehicle with the sensor facing vertically and perpendicular to the road. This road-scanning system gave 180 degree cross-section measurements of the road surface at 0.5 degree intervals, out to a distance of 260 ft from the sensor, for a total of 361 points per sweep. Each sweep was repeated at 37.5 Hz while capturing the infrared reflectivity of the surface impinged by the laser and returning a representative intensity value.

In addition to the LIDAR sensor, a color camera was mounted to the dashboard of the vehicle and manually aligned so that the vanishing point of straight-line driving corresponded roughly to the center of the image. Finally, a steering angle sensor

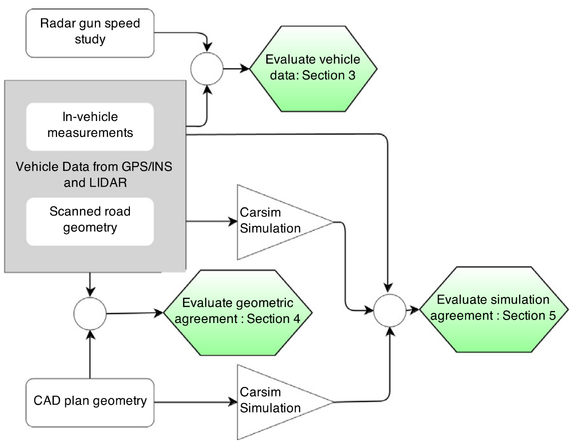

Fig. 1. Outline of methodology for comparison of vehicle simulations between design plans and laser-scanned geometry.