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Development of road grade data using the United States geological survey digital elevation model

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ABSTRACT

Roadway grade significantly affects onroad speed and acceleration, vehicle fuel consumption, vehicle emissions, driver behavior, traffic safety, roadway capacity, and congestion. However, it has always been challenging to obtain grade data at sufficient spatial resolution to use grade as an explanatory variable in transportation models. This paper aims to address this problem by proposing a method to obtain high-accuracy roadway grade data from the Digital Elevation Model (DEM), a nation-wide open data source from the U.S. Geological Survey (USGS). Although DEM data cover most of the nation, data resolution and the presence of roadway cut and fill sections affects spatial grade accuracy and requires a solid strategy to remove or infill these segments. Cubic smoothing spline is applied to minimize the impact of noisy data, and improve grade estimation accuracy. The selection of the key parameter λ in the spline method is also discussed to balance between smoothing out noisy elevation data, and retaining vertical fluctuations along the road. In general, λ is recommended 100–1000 for local roads, and 1000–10,000 for highways to maintain small average estimation error. The relationship between optimum λ that minimizes root-mean-square error (RMSE) and road fluctuations is also explored, which can be used for λ selection. Using real-world measurements as ground truth, the grade results generated from the DEM achieve an average estimation error of 0.5–0.58% for local roads, and 0.21%-0.23% for highways, depending on the resolution of the DEM data used. The results demonstrated the validity and applicability of DEM in generating high-accuracy roadway grade data.

1. Introduction

Roadway grade data are valuable for a variety of transportation and vehicle performance analyses, and roadway design applications. The Highway Capacity Manual (TRB, 2010) provides truck speed performance in response to different road grade values, to reflect that the operating performance of heavy-duty vehicles is significantly reduced by steep grade and grade length. In addition, road grade has been proven to significantly influence vehicle energy use and emissions, at both regional (Barth and Boriboonsomsin, 2009; Levin et al., 2014; Wood et al., 2014a; Sentoff et al., 2015; Zhu et al., 2016) and individual vehicle levels (Barth and Boriboonsomsin, 2009; Franzese and Davidson, 2011; Wyatt et al., 2014; Wood et al., 2014a; Zhang et al., 2015). Previous studies also show that crash rates on steep grade sections are significantly higher than for level sections (Glennon, 1987; Yu and Abdel-Aty, 2014). The research from Hamdar et al., (2016) indicated that driver behavior is less influenced by weather conditions than roadway challenges, including vertical and horizontal changes.

However, road grade information has always been a challenge to obtain, especially at a large spatial scale, due to the lack of

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consistent data sources and methods to process these data. Thus, road grade is commonly omitted from most analyses. For example, in the Motor Vehicle Emission Simulator (MOVES), the approved regulatory model for estimating emissions from the vehicle fleet in air quality analysis (USEPA, 2016), road grade is assumed to equal zero when analyses are conducted at the national and regional-level. This is because road grade data were either not collected or were not paired with real-world vehicle second-by-second driving data (Sentoff et al., 2015).

This study explores the use of the Digital Elevation Model (DEM), an open-source elevation database that is publicly available across the United States, free of charge (USGS, 2016) to estimate road grade. Because of its wide coverage, DEM has the potential to generate road grade estimates at various scales, and be used to append the grade information onto vehicle GPS trajectories to analyze the influence of grade on vehicle activity, vehicle crashes, energy use, and emissions from macro-scale to micro-scale analysis. In this paper, we provide a discussion of DEM data and its applications along with an analysis regarding the feasibility and effectiveness of generating road grade based on USGS DEM data. Later, we introduce a methodology for developing road grades using DEM data and compare results to field-collected road grade measurements. In particular, we describe the performance of the method including elevation extraction from DEM, cleaning and infilling to replace erroneous elevation data, smoothing noisy data with the cubic spline method, and distance-elevation derivation to generate road grade. The selection of a key parameter λ in the cubic spline method used for data smoothing is also discussed to properly balance the smoothing of noisy elevation data versus maintaining the accuracy of vertical fluctuations along the road. The last section provides conclusions and recommendations for future research.

2. Literature review

2.1. Vehicle On-board equipment

Road grade information can be measured using vehicle on-board equipment, including accelerometers (Bonnedahl, 2010; Ikwut-Ukwa, 2001), vehicle sensors (Sahlholm et al., 2007), barometric altimeters (Parviainen et al., 2009), and Global Positioning Systems (GPS) (Bae et al., 2001; Boroujeni et al., 2013; Boroujeni and Frey, 2014; Ogaja, 2011, Awuah-Baffour et al., 1997). Accelerometers installed in a vehicle can provide road slope data, but the measurement is noisy because vehicle acceleration and vibration associated with vehicle movement (unrelated to road grade) interfere with the readings (Rogers and Trayford, 1984). The barometric altimeter technique uses the relationship between atmospheric pressure and altitude to calculate elevation changes, and the road grade can be derived from the elevation profile (Xia et al., 2015), but the accuracy is questionable because the pressure value does not solely depend on the elevation (ambient temperature and pressure vary with meteorology in space and time). GPS data loggers can also be used to measure location and elevation data (Boroujeni and Frey, 2014) although the resolution is relatively low. Vertical elevation errors from GPS are much larger than horizontal errors and can be negatively impacted by signal reflection from nearby buildings, trees, or bridges, (Wing et al., 2005; Awuah-Baffour et al., 1997), or when satellite constellation changes (number and angle of satellites, which affect position calculation accuracy). Road grade is so sensitive to elevation changes that regular GPS loggers alone cannot meet the resolution requirement. Systems built for collecting road grade data usually combine GPS loggers with other equipment (i.e., sensors, barometric altimeter, or accelerometer), because GPS is more robust when recording horizontal positions (longitude and latitude) than the vertical position (altitude). For example, if sample size is large enough to ensure the precision, a GPS logger with barometric altimeter can effectively measure road grades (Boroujeni et al., 2013). Other examples include the GPS-vehicle sensor systems (Sahlholm and Johansson, 2010), and the GPS-accelerometer system (Cheng et al., 2012). Although differential GPS (DGPS) can reduce common errors related to satellite signals when using lower cost GPS loggers (Ogaja, 2011), the accuracy can still be affected by structures and tree canopy (Holden et al., 2001) and DGPS is much more expensive than conventional GPS equipment. Despite the technical concerns, the main limitation of using on-board equipment for collecting road grade data is spatial coverage, given the cost and effort to collect such data for the large networks used in regional and national vehicle energy consumption and emission analysis.

2.2. Design drawings and LiDAR

Road grades can be directly extracted from the road design drawings. However, design drawings are not easily obtained, and may only be available only for large road projects such as freeways, bridges, arterials, and interchanges. In addition, during roadway construction, grades may deviate from original design specifications in the pre-construction drawings due to the modifications or other possible implementation issues (Zhang and Frey, 2006). Sometimes, "as-built" drawings are prepared to reflect the final construction design, but these specifications also may not be precise.

Road grade data can also be collected through the light detection and ranging (LiDAR) systems, using aircraft- or on-road vehicle-mounted laser to measure the topographic data (Heywood et al., 2006). LiDAR can provide accurate terrain profiles for estimating roadway grades on highways and arterials (Zhang and Frey, 2006). However, the cost is relatively high (Hummel et al, 2011), and the accuracy on local roads can be affected when trees block the signal, or when roads fly over railroad crossings rivers, and canyons (Wood et al., 2014a).

2.3. Open source elevation data

Compared with the data collection methods listed above, there are several open-source elevation data sets that are available at little, if any, cost. Many of these data sources have a wide-scale of spatial coverage, including Google® Elevation Data and DEM. For