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Methodology for safety improvement programming using constrained network-level optimization

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ABSTRACT

This paper develops and implements a decision support framework that prescribes and prioritizes cost-effective safety improvements at deserving locations under funding constraints, economic and comprehensive crash cost methods, at rural two-lane highway sections. The framework is demonstrated using Indiana's 7700-mile rural two-lane network. For sections that are both deficient and hazardous under unconstrained budget and economic crash cost method, it was determined that $55 M is needed. Assuming a safety budget of $1 M/year over a 5-year period, it was found that 170–180 crashes (translating to $8–15 M) could be prevented. If the annual budget is increased to $2 M/year over a 5-year period, 244 crashes (translating to $12–26 M) can be prevented. Monetary amounts are in Year 2000 constant dollars. Overall, the results suggest that perpetual increases in highway safety improvements spending are not likely to be accompanied by a commensurate reduction of crashes at rural two-lane highways. In other words, there is a ceiling to the effectiveness of engineering safety countermeasures, and therefore non-engineering countermeasures such as safety education and enforcement must be sought to complement the engineering efforts at rural two-lane highways.

1. Introduction

In many countries, a large percentage of highways are plagued with operational and safety deficiencies arising from outdated designs in face of increasing traffic volumes (Lamm et al., 2006; OECD, 1986). For rural two-lane highways in particular, this issue is particularly critical because such roads are often characterized by inadequate road geometry, driver information deficiencies, lack of passing opportunities, and traffic conflicts due to driveways (McCree, 1988; Vogt and Bared, 1998), particularly when viewed vis-à-vis existing engineering standards, (AASHTO, 2004). This situation is further exacerbated by the fact that rural two-lane roads typically constitute a dominant percentage of the national road network at most countries. As is the case for other highway classes, safety performance at rural two-lane roads is a culmination of several factors including engineering features, driver attributes, vehicle characteristics, enforcement levels, and the environment. In the United States, for example, most rural two-lane roads are several decades old (since construction) and are in need pavement or shoulder replacement, among other safety-related improvements (Zegeer and Deacon, 1987). Furthermore, most of such roads were designed and built to standards that have become outdated vis-à-vis current design policy.

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The pervasive safety deficiencies of rural two-lane roads translate into numerous fatalities and injuries for users of these highways. In most countries, two-lane rural roads make up about 90 percent of rural networks; these roads account for over 60 percent of highway fatalities worldwide, approximately 500,000 people per year (Lamm et al., 2006).

A desirable course of action would be to reconstruct (or at least rehabilitate) all rural two-lane highway sections to standards that are consistent with established design standards. However, the sheer volume of such undertaking is clearly not within the financial capabilities of most national, state, or local governments. On the other hand, allowing the roads to operate under their current geometric deficiencies is also not an attractive option: increases in crashes, vehicle operating costs, delays and inconveniences arising from the existing operational deficiencies often translate into driver frustration and lost time which may in turn exacerbate existing safety deficiencies that already exist due to sub-standard geometry and inadequate safety hardware. Obviously, it would be desirable to focus attention on areas that are identified as needing urgent intervention. In this regard, highway agencies face the task of developing long-term programs that prioritize and select rural two-lane road sections for needed safety improvements. In this paper, the focus is on the engineering factors (particularly, geometric characteristics) which, for most rural two-lane highways, exhibit deficiencies.

This paper seeks to establish a safety program for a rural two-lane network, to prescribe what safety project should be carried out, at which section, and at which year such that the safety funds can yield the highest returns (crashes reduced) per dollar of spending. This paper's demonstration of the safety decision-support framework is expected to help highway agencies to establish and evaluate decisions that are intended to reduce highway crashes. Given the increasing usage of rural highways, even a marginal impact of such benefits can be significant in terms of the reduction of crash frequency and/or severity and other secondary or indirect benefits. The paper focuses on rural two-lane roads only and three (3) functional classes were studied: Rural Collectors, Rural Minor Arterials, and Rural Principal Arterials on the state highway system. A rural area is a census place with a population less than 5000. A two-lane road is one whose cross-section is characterized by a single lane for traffic in each direction and the lanes may be marked or unmarked.

The importance of road safety programming cannot be overemphasized. The vast majority of road systems in any country or state are dominated by rural two-lane roads and that the traffic safety situation is more critical at such roads compared to other road classes. As we noted in the first paragraph of this section, with regard to geometric characteristics of rural two-lane roads, the current situation leaves much to be desired. As such, any effort geared at addressing the safety problems at rural two-lane roads using a programing approach is expected to accrue significant benefits to a large percentage of any road network. First, there are benefits associated with tort risk management: design and maintenance decisions based on budgetary or other economic constraints are generally seen as discretionary in nature and consequently are generally immune from tort suits. However, as demonstrated in past cases, a transportation agency may argue that its failure to remedy a defective design is due to funding priorities but can be held liable if the agency presents no evidence on planning or ordering of priorities (Thomas, 2003). In this regard, the development of a program that identifies problems for rural two-lane highway system develops safety needs assessments and establishes priority schedules for safety investment at such roads would be helpful for pre-emptive risk management. By providing evidence on planning and programming of investments, such programs will place the state in a better position to defend itself against claims related to highway engineering deficiencies. Secondly, a programing approach can yield results that throw more light on safety-related policy issues including the relationship between safety expenditure and corresponding cost-effectiveness and crashes saved; whether there is a ceiling to the effectiveness of engineering safety countermeasures at rural two-lane highways and thus he importance of non-engineering countermeasures in eradicating the crash problem at rural two-lane highways.

The paper focuses on road segments. A "segment" is defined as a section of road between major intersections or where there is a significant change in geometric characteristics. The segments for the study were taken from the Indiana Safety Management database. Those sections have lengths that may be considered as being long enough to obviate the problem of zero inflation, but short enough to ensure maximum consistency of geometric features within each section. Average trends indicate that approximately 70% of all crashes on the state highway network occur at road sections while 30% occur at intersections. Due to differences in dynamics of crash occurrence at intersections and the lack of reliable data on intersection crashes at the time of the study, intersection crashes were excluded. For determining which crashes actually occurred on the roadway segments, and not at the adjoining intersections, a benchmark value of 50 ft. was used to help differentiate road section crashes from intersection crashes. The crash severity levels considered are: fatal, injury, and property-damage-only. In a case study to demonstrate the methodology, data from rural two-lane roads in the state of Indiana are used in this paper. The methodology can be replicated for a network of intersections or a network of both intersections and road segments.

2. Review of pertinent literature on road safety project programming

Several approaches have being reported in the literature for developing safety improvement programs in rural and urban areas. Multi-criteria models with fuzzy-analytical hierarchical process (AHP), fusion model by game theory, and branch and bound algorithms are the most common founded methodologies. Yu and Liu (2012) investigated the technical, economic, and social impacts of prioritizing safety improvement projects using a risk-based multi-criteria approach (fuzzy-AHP) that was integrated with an optimization module; their methodology had the advantage of effectively preventing the arbitrariness in determining the weights for multiple ranking criteria and easily synthesizing the final score of each candidate project for selection. In a study with similar objectives as the Yi and Li study, Fang and Guo (2013) considered the decision-making