Optimization of Safety Treatments Selection: Case Study for Provincial Road Network in Jaffna

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Abstract: Sri Lanka's road network is divided into national, provincial, and local authority roads based on functional and management responsibilities. Provincial roads, classified as class C and D, connect urban and rural areas, supporting social and economic needs. Many of these roads are in poor condition with minimal safety measures, and there is a lack of analytical tools to select appropriate safety treatments within the available budget. This study introduces a methodology to systematically determine safety treatments for selected roads to enhance safety performance. The safety performance of provincial roads is evaluated using the Cumulative Safety Index (CSI), which reflects existing road issues. The actual accident data is converted to EPDO value and computed CSI value is validated. A framework is suggested to incorporate safety performance into the Highway Asset Management System, specifically within the optimization analysis. This framework aims to minimize the average network Cumulative Safety Index (CSI) as its primary objective. The cumulative Safety Index is reduced with the implementation of safety treatments. Even though all the safety treatment are not be able to implement due to the lack of funding. Safety treatment strategies are implemented. The results show that roads with significant safety concerns are prioritized in budget allocation with a feasible combination of safety treatments. The results shows average network Safety Index is gradually decreased with the increase of available budget. This methodology provides a crucial analytical tool for the Highway Management System, simplifying the integration of road safety performance in provincial road network management.
Keywords: Provincial Road, Safety Index, Equivalent property Damage Only, Root Mean Square Error, Optimization, Safety Treatments.

Introduction

In Sri Lanka, roads are the primary mode of transport, handling 90% of passenger travel and 98% of freight transportation. The country has 15,500 kilometers of provincial roads and 16% of road network comprises provincial road, which are managed by provincial councils and provincial road development authorities. Provincial Road Development Department manages the Northern Province's road network, where about 90% of the roads are in poor condition due to inadequate maintenance [1]. Road accidents are a serious public issue, steadily increasing with time in Sri Lanka. The Northern. After the civil war, the region's economy improved, resulting in more road users and increased motorization, which significantly raised the rate of traffic accidents. Compared to other countries, Sri Lanka lacks an effective highway maintenance system, leading to economic inefficiencies and resource misallocation. Authorities are unaware of optimal maintenance strategies, and there is no established management system for provincial roads. The region's economic and social growth has increased road users and accident rates on provincial roads. This study presents safety improvement strategies are implemented in every road within the entire road network within the constraints of the available budget, facilitated by the introduction of optimization approaches. Safety performance of each corridor is calculated with the safety index.

Despite diverse of safety issues in provincial road network, geometric safety issues are only focused for this study. Highway management has struggled for a long time due to a lack of proper finance. With the advent of optimization approaches, a cost effective set of safety improvement strategies are implemented for each road in the overall network.

Research Background

Accidents in low volume roads

Based on the analysis of crash types and percentages by accident severity from the 297B police record form, multi-vehicle crashes occur more frequently on low-volume roads. In the low volume accidents, motorcycles are one of the most commonly involved vehicles. In Sri Lanka, motorcycle usage has risen dramatically in recent years. The second greatest percentage of casualties are three-wheelers. Pedestrians are the third most common element type. In Sri Lanka, the accident investigation method often fails to accurately identify relevant highway attributes contributing to accidents. In 2017, roadway-related factors were identified as causes in fewer than 1% of all reported incidents [2].

Identification of safety issues and implementation of counter measures

A team conducts a road safety audit, systematically identifying safety issues on Low Volume Roads (LVR). They assess various hazards during their road travels, including improper signage, limited roadside space, alignment issues (horizontal and vertical curves), inadequate pedestrian facilities in high pedestrian areas, rail crossing problems, vertical drops, unprotected culverts and bridges, and open drains[3]. Safety inspections are widely recognized as an effective tool for identifying potential road hazards and are becoming standard practice globally. Despite their subjective nature, a high level of agreement among inspectors has been demonstrated. This was confirmed by ratings of safety issues on 200 road segments by two sets of professionals. These ratings use checklists covering key safety elements on two-lane rural roads, assessed in 200-meter increments in both directions[4]. Road expansions in Bangladesh could significantly reduce fatalities with a high benefit-cost ratio. In Malaysia, the introduction of bike lanes proved highly effective in saving lives, also showing a favorable benefit-cost ratio[5].

Safety Evaluation and validation method

Safety performance of roads were evaluated in different ways in several highway agencies[6][7]. Safety performance is assessed using the road safety index, which considers exposure, probability, and consequences. Exposure quantifies the extent to which road users are subject to specific safety issues, evaluated based on traffic volume at the location. Probability measures the likelihood of a collision due to the safety issue. Consequences quantify the severity level, influenced by factors such as vehicle speed, potential speed differentials, vehicle size mix, and roadside hazards. Accident data was utilized to validate the estimated road safety risk index. The Potential for Improvement (PFI) indicator is defined as the difference between the current and predicted collision frequencies at a given location. A viable collision prediction model, developed using Generalized Linear Modeling (GLIM), provides the predicted collision frequency, which is further refined using the Empirical Bayes (EB) approach [8]. The safety performance of rural roads in Sri Lanka was evaluated using the Cumulative Safety Index (CSI) for low-volume roads and the International Roughness Index (IRI) for pavement conditions. The Safety Index was calculated based on exposure, consequences, and probabilities for each safety issue, with a cumulative safety index determined for each road. CSI values were used to assess the correlation between accident numbers and road sections. Validation involved comparing CSI values with available crash data. Severity levels of crashes, including fatal, grievous, and non-grievous, were combined into an Equivalent Property Damage Only (EPDO) scale, weighted by the anticipated economic costs of each crash type[3][6].

Optimization approach used in highway asset a mangement system

Since 1987, pavement management systems have employed various optimization methods, including integer goal programming, linear programming, dynamic programming, linear integer programming, and genetic algorithms. These methods primarily aim to enhance pavement conditions within budgetary constraints for maintenance and restoration [9].

A Multiple Objective Optimization (MOO) was conducted to minimize the cumulative safety index (CSI) and IRI value within the allocated budget. Single Objective Optimizations (SOO) identified anchor points in the solution space. Three maintenance and three safety improvement operations were employed. The network status of each segment after each treatment type and the CSI value after each safety improvement operation must be forecasted prior to executing the optimization model. The goal was to minimize the average network IRI and CSI within budget constraints. Results indicated that reasonable pavement condition improvements can be achieved by implementing a suitable combination of safety treatments within the budget [3][6].

The study introduces a methodology to determine a safety index for evaluating safety performance on provincial roads in Sri Lanka. The methodology employs the Cumulative Safety Index (CSI) within an optimization approach that integrates road safety into the broader maintenance scheme. Safety performance function, Branch Index Risk (BIR) and the Section Index Risk (SIR), Road infrastructure safety management, Road Safety Development Index (RSDI), Safety performance function and Analysis of Hierarchy Process (AHP) are the methods used in the highway asset management system. Even though the suggested methodology in this study is CSI methodology which is specifically designed to function effectively in conditions where data is limited, providing a significant advantage over existing methods that require extensive data inputs. Unlike traditional safety indices, which often operate independently of maintenance. The use of an optimization approach to determine the best allocation of resources for safety improvements is innovative. The proposed framework simplifies the evaluation of road safety, making it more accessible to regions with limited technical and institutional capacity. the existing methods that may be too complex for practical use in these contexts.

Methodology

Introduction to the Study area

This study focused on the provincial road network in the Northern Province, specifically within the Jaffna district. The Provincial Road Development Department is responsible for maintaining this network. In the Jaffna District, approximately 3.5% of the land area is dedicated to public roads [10]. Following the civil war, the population density surrounding the provincial road expanded dramatically as a result of economic, infrastructural, and social growth. The roads in Northern Province, particularly in Jaffna, are largely deteriorated due to inadequate maintenance. However, efforts are underway to renovate and maintain the country's highways. Despite the poor condition of most roads, construction on several provincial roads is ongoing. Each road is a single carriageway with a maximum width of 6 meters. The provincial roads examined in this study connect national roads with local roads in agricultural regions and densely populated. The geographical conditions and landscape remain consistent throughout the research area.

Data Collection and Method

Define Safety issues - The road segment was selected for the identification of prevailing road safety issues in each road network. There are many safety issues under different issue categories. Even though four prioritized safety issue types were considered in this study based on the risk to road users, especially in Jaffna district, under geometric safety issues in each road network. A safety audit was carried out systematically to find the issue type in each road segment that causes safety hazards. Traffic related data- Average Daily Traffic (ADT) is calculated based on the average of seven-day traffic counts. The traffic counts and surveys provide data on maximum traffic volumes, including both motorized and non-motorized vehicles, with detailed vehicle composition counts for the selected road and each safety issue location. Vehicle speed data, including the maximum speed limit for the chosen road and the speed limits at each safety issue location, were obtained from the safety audit.

Accident data- Accident data, categorized by collision type (fatal, grievous, and non-grievous), were obtained from police records compiled over one year. For each reported and investigated accident, the Sri Lanka Police complete Accident Form 297B. Although the form does not specify the fundamental causes of accidents.

Development of Safety Index

The Safety Index generated to evaluate safety performance of the road segment with the multiplication of fundamental elements, Exposure, Probability and Consequences. Safety Index = Function of (exposure, probability and consequences). Since the exposure of non-motorists is high in Jaffna, both motorist and non mpotorists were considered in the deamination of exposure scaling system. Exposure at specific road features and the maximum volume of exposure at each locationwere determined simultaneously. The exposure score ranged from zero to three.

$$E_{\mathrm{m}} = \left(V_{\mathrm{i(m)}}/V_{\mathrm{m}}\right) \times 3 \qquad (1)$$

$$E_{\mathrm{n}} = \left(V_{\mathrm{i(n)/}}/V_{\mathrm{n/}}\right) \times 3 \qquad (2)$$

Where;

E_m= Exposure of motorists

$V_{i(m)}$=Volume of motorist at the location of a specific road feature i

V_m= Maximum volume of motorist on the corridor

E_n = Exposure of non-motorists

$V_{i(n)}$ =Volume of a non-motorist at the location of a specific road feature i

V_n=Maximum volume of non-motorist on the corridor

Table 1 explained the exposure of the location with the scale ranging from 1 to 5[6].

Table 1: Exposure scale

Exposure of motorist	Exposure of Non motorist		
	0-1	1-2	2-3
0-1	1	2	2
1-2	3	3	4
2-3	4	5	5

Probability is the measure of the likelihood of a vehicle being involved in an accident at a specified location of issue. Exposure scale of a risk was obtained from the developed guideline for each safety issue identified in the specific corridor. The probability component of risk was obtained by using the guidelines developed for each safety issue and by making an assessment of each road feature using the point scale. The probability score for each safety issue was established by considering the impact of infrastructure attributes and safety issues, alongside the guidelines provided by the International Road Assessment Program (IRAP) and the Infrastructure Risk Rating (IRR) manual [7].

Table 2: Probability scale

Probability of occurrence	Score
Rare	1
Unlike	2
Moderate	3
Likely	4
High	5

Consequences in the measure of degree of severity influenced by speed of vehicle, size and road side hazards. Speed factors considered to manipulate consequences as mention in (3)[8]. The score ranging from zero to a maximum of 5.0.

Where;

$$C_{\mathrm{i}} = PS_{\mathrm{i}}/PS_{\max} \qquad (3)$$

C_i=Consequences in location of safety issue

PS_i=Posted speed at the location of safety issue

PS_{max}= Maximum posted speed in the corridor.

Table 3: Score of consequences

Score	Severity	Score
0-1	Insignificant	1
1-2	Minor	2
2-3	Moderate	3
3-4	Major	4
4-5	catastrophic	5

Safety Index in each safety issue (SIi) was computed with (4)

$$SI_i = E_i \times P_i \times C_i \tag{4}$$

SI_i= Safety index of issue i
E_i = Exposure of issue i
P_i = Probability of issue i
C_i = Consequences of issue i
The cumulative safety index is the combination of each safety issue occurring in corridor k, which was calculated for 1 km segments of each roads. Cumulative Safety Index for the roads were computed using Equation (4).

$$CSI_c = \sum_{i=1,} I \sum_{t=0,T} (SI_{it})_c \tag{5}$$

Where CSI_c= Cumulative Safety Index for corridor c,
(SI_{it})=Safety Index for t_{th} occurrence of i_{th} safety issue,
I= number of safety Issue types,
T= Number of occurrences of each safety issue types.

Development of Regression Model

Actual data of the accidents for each road segment was collected from the accident form to develop a regression model. Since the severity level of each crashes are classified as fatal, grievous, and non-grievous and property damage only, it is need to be represented in a single standard scale according to the weightage of severity[3]. Equivalent Property Damage Only (EPDO) factor which was allocate higher factor to fatalities and decrease along with grievous, non-grievous and property damage only. Crash economic cost analysis in Sri Lanka was used to develop an equation for Equivalent Accident Numbers (EAN) with respect to the severity level of property damage only[11]. Equation (6) shows the weightages of severity level relative to EPDO[6].

$$EPDO(A) = 14.6F + 8G + 1.14N + D \tag{6}$$

Where $EPDO(A)$ = Actual EPDO of the road,
F= Number of fatal crashes,
G= Number of grievous crashes,
N= Number of Non- Grievous crashes
D= Number of property damage only,

Actual EPDO has consistently increase with the increasing of CSI value. It has noticed that the R-squared value is 0.9038, which is a good fit of the line to the data. After computing the actual EPDO using available accident data, multiple regression analysis was employed to determine the relationship between the actual EPDO and a computed CSI. R-Squared was 0.95 and the significance level of all factors was less than 0.05 under the confidence interval of 95%. Equation for the estimated EPDO was obtained from the results of regression analysis is shown in (7)

$$EPDO(E) = 4.271 + 0.032X_1 + 0.019X_2 + 0.032X_3 + 0.01X_4 \tag{7}$$

where $EPDO(E)$ = Estimated EPDO for the road, X_1= Cumulative safety index for issues on sight distance, X_2 = Cumulative safety index for issues on road side space, X_3= Cumulative safety index for issues on Access, X_4= Cumulative safety index for issues on pedestrian facilities.

Validation of Cumulative Safety Index

Estimated EPDO then compared with the actual EPDO which was developed with the available crash data. Correlation between estimated and Actual EPDO was 0.965 as shown in Figure 1. Furthermore Root Mean Square Error (RMSE) was measure to compare estimated and actual EPDO values. The result obtained from the RMSE is 1.16.

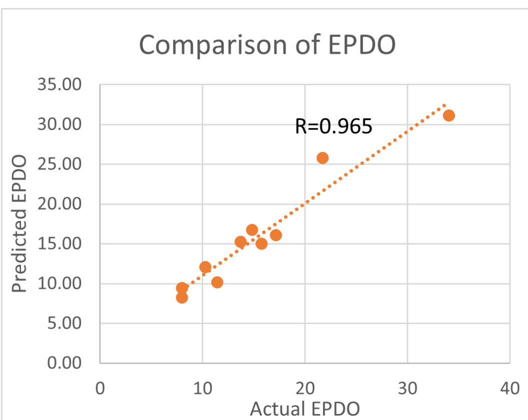

Figure 1: Comparison of Predicted and Actual EPDO values

Implemented safety treatments in the safety issue locations

A field evaluation was conducted to identify countermeasures for the relevant safety issues. Based on the prevailing safety conditions, there are various safety improvement treatments. All of the treatments are unable to be implemented in the road due to a lack of funding for the project. The treatments were separated into strategies in order to find a feasible solution for safety treatments under the constraint of budget and optimum CSI after the implementation of safety treatments. Strategy 1: provide sign boards, lane markings, pedestrian crossing marking, cyclist facility marking, pedestrian sign board and remove obstruction. Strategy 2: construct pedestrian facility, widen road and construct cyclist facility. Strategy 3: Combination of strategy 1 and Strategy 2.

In order to define the set of safety treatments to be implemented on provincial roads, safety performance was utilized as an objective function, and budget was used as a constraint. Feasible safety treatment for the available budget was identified in the optimization approach as shown Equation (7) and (8)

$$\text{Minimize } Q = \frac{\left[\sum_{s=1}^{3}\sum_{i=1}^{n} CSI_{si} \times X_{si}\right]}{\sum_{i=1}^{n} L_i} + \frac{\left[\sum_{k=1}^{4}\sum_{i=1}^{n} CSI_{ki} \times \left(1-\sum_{s=1}^{3} X_{si}\right)\right]}{\sum_{i=1}^{n} L_i} \quad (8)$$

Constraints;

$$\left[\sum_{s=1,3}^{i=1,n} CSI_{si} \times X_{si}\right] \leq B(Budget) \quad (9)$$

CSI_{si}< 10 were not considered in the optimization Where;

Q = Average cumulative safety index of the road network. CSI_{ki} = Cumulative Safety index for issue type k for road i CSI_{si} = Cumulative safety index after applying safety strategy s in the road i

Li = Length of road i

X_{si} = Decision variable for strategy$s$ applied to road i

C_{si}= Cost for applying safety improvement strategy s for road i

s= Safety Treatment strategies

B= Budget allocation for the project

n= Number of roads
L=Total length of road network in km
CSI after the implementation of safety counter measures was calculated. The Figure 2 illustrates the process of generating feasible solution safety treatment strategies by taking into account the objective function and constraints of the optimization. The same optimization process was used for the different available budgets.

Figure 3 display the optimization results for various budgets. The results demonstrate that as the budget is raised, the objective function average network CSI will gradually reduce. It can be concluded that improvement in Average network CSI with the increase of available budget. Additionally, this methodology can also be used to select suitable combination of safety treatments and maintain the provincial road network, ensuring that road users travel safely and comfort. The same optimization process was used for the different available budgets. Figure 3 display the optimization results for various budgets. The results demonstrate that as the budget is raised, the objective function average network CSI will gradually reduce.

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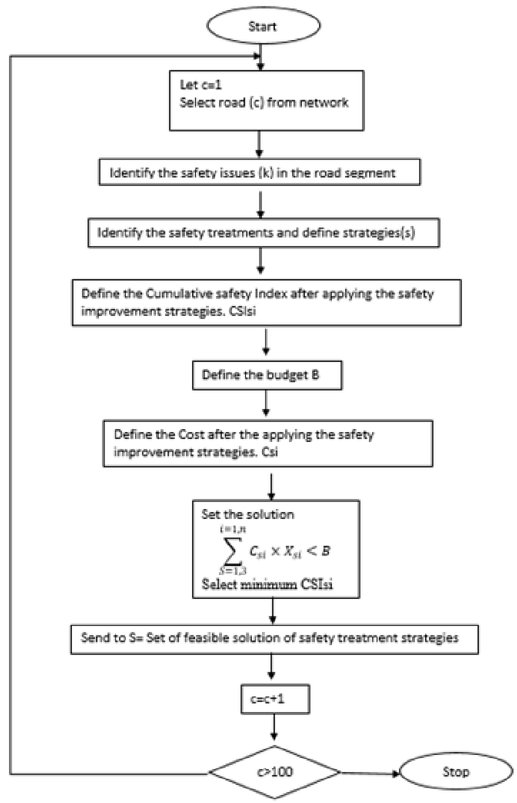

Figure 2: Framework to incorporate Safety in Highway Asset Management System

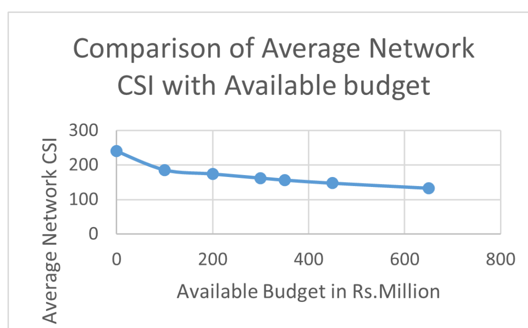

Figure 3: Management Comparison of Average Network CSI with available budget

Conclusion & Discussion

Improving highway management is crucial for road safety and can reduce accident costs. This research provides a methodology for selecting safety treatments within highway asset management systems for provincial roads, focusing on the Jaffna district, a peninsula in northern Sri Lanka. Safety performance was evaluated using CSI value. The linear regression study revealed that there is a high correlation between CSI and traffic accidents. The Equivalent Property Damage Only Factor was used to account for road accidents. RMSE was used to compare the fitness between Actual and Estimated EPDO. An optimization model was used to develop a combination of safety treatment strategies for each road. CSI, cost, and average network CSI were defined. Optimization results show the feasible solution of safety treatment strategies. The optimization results show a significant reduction in average network CSI after the implementation of safety treatment strategies.

The major limitation and challenge in this study is the availability and accuracy of available accident data, particularly the course of accidents mention in the accident forms. Absence of accident data case the accuracy of the results and validation. Many accidents are unreported to police. Safety audit takes time to identify each issue point. Identification location speed and traffic volume in many places in one segment of road is major challenge. The suggested methodology facilitates budget allocation analysis and estimation for the provincial road network in order to include safety evaluation in the highway management system. However, the proposed methodology provides a crucial analytical tool for highway asset management systems to incorporate network-level safety improvement evaluation into the provincial roads in Sri Lanka.

Future Recomendation

Improvement may include the addition of other safety issues which fall under significant categories, such as pavement condition, safety hardware, and road features in the study area. The suggested guideline scaling approach for the probability component of the Safety Index calculation can be improved by taking into account other safety issues. Identify proper mechanism to identify the issue location, specified speed, traffic volume at the particular location in each segments. All the accidents should be reported to improve the validation of the results in each location.

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