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Development of a lane change risk index using vehicle trajectory data

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ABSTRACT

Surrogate safety measures (SSMs) have been widely used to evaluate crash potential, which is fundamental for the development of effective safety countermeasures. Unlike existing SSMs, which are mainly focused on the evaluation of longitudinal vehicle maneuvering leading to rear-end crashes, this study proposes a new method for estimating crash risk while a subject vehicle changes lanes, referred to as the lane change risk index (LCRI). A novel feature of the proposed methodology is its incorporation of the amount of exposure time to potential crash and the expected crash severity level by applying a fault tree analysis (FTA) to the evaluation framework. Vehicle interactions between a subject vehicle and adjacent vehicles in the starting lane and the target lane are evaluated in terms of crash potential during lane change. Vehicle trajectory data obtained from a traffic stream, photographed using a drone flown over a freeway segment, is used to investigate the applicability of the proposed methodology. This study compares the characteristics of compulsory and discretionary lane changes observed in a work zone section and a general section of a freeway using the LCRI. It is expected that the outcome of this study will be valuable in evaluating the effectiveness of various traffic operations and control strategies in terms of lane change safety.

1. Introduction

A widely used traffic safety assessment method involves using actual crash data that incudes crash frequency and severity information. Various statistical modeling techniques have been applied to identify safety-related issues and develop countermeasures based on analyzing crash data. However, the use of crash data for safety analyses has limitations because traffic crash events are rare and random, which has led to long-term data collection efforts to obtain sufficient samples that directly affect the statistical significance. Therefore, an unavoidable drawback exists due to the crash sampling issue in assessing traffic safety in a more proactive manner, although actual crash-based methods are objective. A promising alternative is to use surrogate safety measures (SSMs) that quantify the potential of crash risks (Hydén, 1987). The advancement of sensors and communication technologies allows for identifying hazardous events readily, which are highly correlated with crash occurrence, based on analyzing vehicle trajectory data. To date, various attempts to derive robust measures to capture hazardous events have been made in the field of traffic safety.

Time-to-collision (TTC) is one of the most widely used SSMs for the purposes of traffic and vehicle safety. TTC is the time remaining to avoid an accident, from the time the driver takes an action to the point where the accident can occur (Hayward, 1971). It responds sensitively according to changes in the current position and speed, and it is possible to predict whether collision occurs at a specific point in time when the speed and direction of a subject vehicle does not change. TTC can be calculated only when a following vehicle is faster than a leading vehicle. Nevertheless, TTC is the most frequently used SSM because it is easy for users to understand. The expanded indicators based on the TTC concept include time exposed TTC (TET), time integrated TTC (TIT), and time-to-lane crossing (TLC) (Minderhoud and Bovy, 2001; Van Winsum et al., 2000). Post encroach time (PET) is a measure of the situation in which accidents almost occur; it is the time difference between the time at which a preceding vehicle has passed through one point and the time at which a vehicle traveling in the opposite direction reaches that point (Allen et al., 1978). Because PET reflects the temporal and spatial proximity of vehicles, it can be measured regardless of the speed of the following vehicle, unlike TTC. Measures derived from the PET include gap time (GT), encoding time (ET), and time advantage (TAdv) (Hansson, 1975). As another branch of SSMs, deceleration-based measures are used in various ways. Maximum deceleration (Max D), deceleration-to-safety time (DST), deceleration rate to avoid crash (DRAC), and stopping distance index (SDI) fall into the category of SSMs using deceleration (Gettman and Head, 2003; Hupfer, 1997; Cooper and Ferguson, 1976; Oh et al., 2006). Max D is the maximum deceleration observed in a collision event. The DRAC is the minimum

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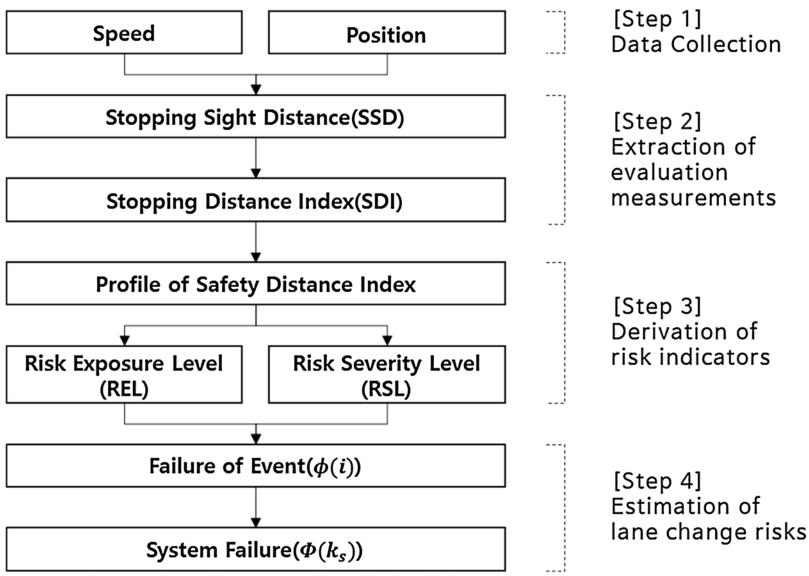

Fig. 1. Overall evaluation framework.

deceleration needed to avoid collision, and the DST is the time a driver with minimum deceleration requires to safely stop to avoid a collision. SDI is a discrete measure used to determine whether a given car-following event is safe by comparing stopping sight distances (SSDs) for the preceding vehicle and the following vehicle. Regarding the identification of potential crash severity, DeltaS is able to indicate the crash severity (Evans, 1994), unlike the aforementioned measures used to capture hazardous events. DeltaS indicates the severity of a latent crash with the maximum speed difference when the conflict between a preceding vehicle and a following vehicle is defined. The severity level of a potential crash can be determined when the speed difference between the preceding vehicle and the following vehicle is larger. As a similar indicator, DeltaV is an index of vector velocity change when an actual vehicle collision occurs and when it is possible to estimate the accident collision energy (Gettman and Head, 2003).

As reviewed above, various SSMs are being utilized for traffic safety assessment. Recent studies have attempted to evaluate the safety of lane change events (Wang and Stamatiadis, 2013, 2014). However, we are not aware of any study to estimate lane change risks by incorporating the amount of exposure time to potential crashes and the expected crash severity level, which motivates out study. The continuous profile of SDIs during lane change, which represents the interactions between a subject vehicle and adjacent vehicles, is further analyzed to extract two risk indicators: risk exposure level (REL) and risk severity level (RSL). The REL indicates how long a subject vehicle is exposed to a hazardous situation that could potentially lead to crash while making a lane change. Meanwhile, RSL represents the severity of the crash that would occur if a subject vehicle does not make the appropriate evasive maneuver. Then, a fault tree analysis (FTA), which is a well-known technique for risk analysis, is adopted to integrate the REL and the RSL. As a result, a new index to estimate the probability of failing to make a safe lane change, which is referred to as the lane change risk index (LCRI), is proposed.

In the transportation field, several studies have used the FTA technique to understand the contributing factors affecting crash occurrence. Joshua and Garber (1992) and Kuzminski et al. (1995) used the FTA method to analyze the relationship between driver, vehicles, environmental factors and traffic crashes. Huang et al. (2000) investigated the cause of accidents using the fuzzy fault tree method to evaluate the safety of railway transportation systems. Kronprasert and Thipnee (2016) constructed a fault tree based on various crash causes and proposed a monitoring system for preventing crashes. Meanwhile, Joo and Oh (2013) proposed an integrated evaluation index for evaluating bicycling environments via FTA using instrumented probe bicycle data.

Vehicle trajectory data obtained from a traffic stream photographed using a drone in a freeway work zone is used to investigate the applicability of the proposed methodology. This study compares the characteristics of compulsory and discretionary lane changes observed in a work zone section and a general section of a freeway.

The proposed methodology, including how to derive the REL and the RSL and how to apply FTA to integrate them, is presented in the next section. Section 3 describes the data used in estimating lane change risks, which are extracted from the drone images. Analysis results and discussion regarding a further application are presented in Section 4. Finally, a summary of this study, further research directions, and the limitations and research issues are provided.

2. Methodology

2.1. Overall framework

Vehicles traveling along a road continuously interact with neighboring vehicles in the current and adjacent lanes. Vehicle interactions lead to various car-following behaviors and to the occurrence of lane-changing events. The analysis of such interactions is of keen interest in evaluating the effectiveness of traffic operations and control strategies. This study attempts to develop a systematic and scientific estimation method for crash risk, which is an outcome of improper interactions. Suppose that the trajectory of a vehicle is the change in vehicle position over time. The proposed methodology continuously evaluates the risk of lane change events using a FTA method. The overall procedure, consisting of 4 steps, for estimating the risk of lane change events is presented in Fig. 1.

The first step is to collect individual vehicle trajectory data, including vehicle positions and speeds. A total of four adjacent vehicles, which include the lead (k_{Le}) and lag (k_{La}) vehicles in the target lane and the front (k_F) and rear (k_R) vehicles in the starting lane, affect the risk when a subject vehicle (k_S) changes lanes, as shown in Fig. 2. The second step is to determine whether k_S is in a safe situation with each adjacent vehicle while changing lanes at every time step. This study uses the stopping distance index (SDI) based on the stopping sight distances (SSDs) of two vehicles. 2.5 s perception and reaction time recommended by the Korean Highway Design Guideline (Korean Ministry of Land, Transport and Maritime Affairs., 2013) were used in calculating SSDs in this study

The SDI is an index for determining the rear-end collision risk based