DEVELOPMENT OF METHODOLOGY FOR ESTIMATING SAFETY BENEFITS OF AUTOMATIC CRASH NOTIFICATION SYSTEMS

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ABSTRACT

The automatic crash notification system (ACNS) is a well-known technology with promising potential to reduce the crash response time (CRT) of emergency medical services. Reducing CRT will contribute to saving the lives of and alleviating the severity of injuries for crash victims. To fully operate the ACNS, it is important to quantify the safety benefits, which is fundamental for justifying public investment. This study proposed a methodology for quantifying the effectiveness of the ACNS and applied the methodology to the Korean freeway system. The proposed methodology consists of three steps. Fist, a statistical model was developed to predict injury severity using ordered logistic regression. Second, the amount of reduced CRT that would result from the ACNS was estimated. The effectiveness of the ACNS, which are defined as the number of reduced fatalities and severe injuries, were derived after considering the market penetration rate (MPR). When the proposed methodology is applied to 2010 freeway crash data, the result that fatalities are reduced by 11.8-18.1% when there is a 100% MPR. The outcomes of this study support decision making for public investments and for establishing relevant traffic safety policies.

INTRODUCTION

"Platinum minutes", "golden hours", and "silver day" are well-known terms that emphasize the importance of rapid medical response to save crash victims' lives *(1-3)*. The results of existing studies reveal significant improvements in life savings when the medical response time is reduced *(4-9)*. In the recent literature, Sanchez-Mangas et al. *(10)* demonstrated that a 10 min reduction of the medical response time could result in a decrease in the probability of death by a third. In accordance with these findings, engineers and traffic safety researchers have made substantial efforts to accurately detect crashes and to rapidly notify crash information to emergency medical services (EMS). Advancements in information technologies, including sensors and communications, allow engineers and researchers to develop more effective technological countermeasures. The automatic crash notification system (ACNS) is a promising technology for reducing EMS response time after crashes. Reducing the response time will contribute to saving crash victims and alleviating the severity of their injuries.

Significant efforts have been made in many countries to employ the ACNS. For example, the National Highway traffic Administration (NHTSA) conducted field operational tests, which have been discussed for future applications *(11)*. The European Commission (EU) has mandated that all new vehicles in Europe be equipped with the eCall system, which is an emergency call that notifies EMS and reduces the medical response time in traffic crash situations *(12)*. In addition to public agencies, academic and private sectors continue to improve the ACNS for increased reliability. Akella et al. *(13)* evaluated the reliability of ACNS by analyzing the received signal strength indicator (RSSI). Delmelle et al. *(14)* analyzed the strength of the received signal to develop a spatial regression tool that evaluates the effectiveness of ACNS technology. Bose et al. *(15)* presented a computational methodology for predicting the post-crash injury severity and relaying injury data to emergency medical services. A commercialized system in the private sector demonstrated the effectiveness of reducing injury severity with the ACNS *(16)*.

One of the important research challenges is to accurately estimate the effectiveness of the ACNS with regard to traffic safety. Reliable assessments of the safety benefits would be useful for establishing and applying policies that will disseminate ACNS technology to reduce injury severity of crash victims. In addition, estimations of the safety benefits are valuable for improving the functionalities of the system and for developing new technologies. These needs comprise the motivation for this study.

The purpose of this study is to estimate the effectiveness of the ACNS by quantifying the reduction in injury severity. The main focus of our study is freeway traffic crashes, as freeway crashes are associated with high fatality rates and severe injuries. Freeways are more dangerous primarily because of higher vehicle speeds than on other road types. Another reason to focus on freeway crashes is that traffic surveillance and management systems on Korean freeways provide reliable crash-related information, such as the crash occurrence time, incident duration, emergency vehicle arrival time, and post-incident management information etc.

This study defines the ACNS-related reduction in the number of fatalities and injuries as the safety benefit. To quantify the safety benefit, a methodology that consists of three steps is proposed. First, a statistical model with ordered logistic regression is developed to predict discrete injury outcomes, such as fatality, severe injury, and minor injury. A variety of variables that contribute to injury severity are employed in the model, including crash response time (CRT), which is defined as the time interval between crash occurrence and the arrival of EMS at the crash location. Second, the reduced CRT that is associated with the ACNS is estimated. The safety benefits of the ACNS are then derived after considering the market penetration rates (MPR).

This paper is organized as follows. In Section 2, an overview of ACNS functionality is provided, and the opportunity to save lives is discussed. The methodology proposed in this study is described in Section 3, and the model development for the application of the proposed methodology and data analyses are discussed in Section 4. This paper concludes by discussing the research results and suggesting future research needs.

OVERVIEW OF ACNS FUNCTUINALITY AND AN OPPORTUNITY TO SAVE CRASH VICTIMS

The ACNS is an effective tool that integrates vehicular and communication technologies to enhance the potential for saving crash victims. The ACNS has two primary functionalities: crash detection and crash notification to EMS providers. A key element for fully operating these functions is an in-vehicle device that can accurately detect crashes and reliably transmit crash information to EMS providers. In addition, for the ACNS to be effective, operations are required to dispatch EMS vehicles to crash scenes. Figure 1 provides a conceptual illustration of the ACNS.

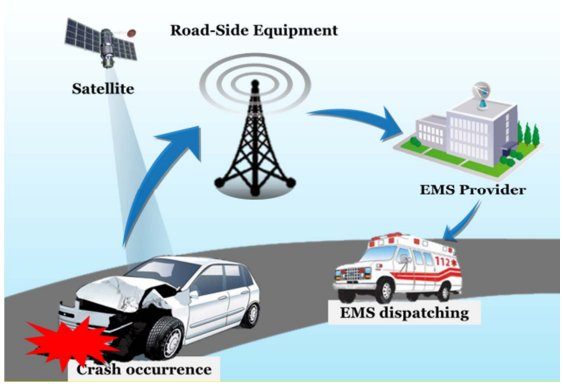

Figure1. ACNS framework

The ACNS saves crash victim lives by reducing CRT. Traffic management centers (TMCs) generally have specific crash management programs, including crash detection, crash verification, crash notification, and emergency dispatching. CRT consists of four time intervals between the crash detection time and the emergency dispatching time. Figure 2 compares CRTs 'with and without the ACNS'. When CRT is reduced with the ACNS, there will be a greater potential to save crash victim lives. Particularly, CNT can be reduced with the ACNS, which is shown in Figure 2. The reduction in CNT with the ACNS makes the safety benefit feasible.

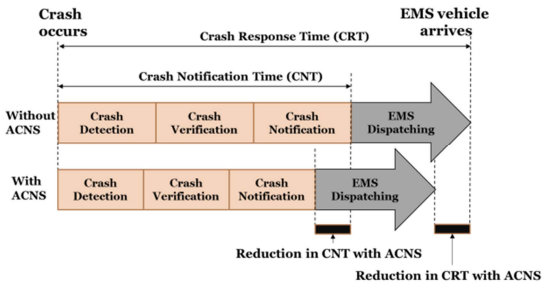

Figure2. Crash management process

Therefore, a key element for estimating the safety benefits is to obtain a reliable reduction in CNT (ΔCNT). As was reported in the aforementioned literature, CRT is highly associated with injury severity, it is important to identify their relationship between CNT and CRT. Large reductions in CRT can lead to substantial safety benefits. Remaining problems include determining how to model the relationship between the probability of injury severity and CRT and estimating reduced CRT with the ACNS. Detailed descriptions of the proposed method are presented in the next section.

METHODOLOGY

The methodology for quantifying the safety benefit involves estimating the number of crash victims

who will be saved or less injured with the ACNS. The proposed methodology consists of three steps. The first step is to identity the effects of various contributing factors on the injury severity of crash victims. A statistical modeling approach can be applied to derive a functional relationship between these factors and injury severity. Because the ACNS reduces CRT in the pre-hospital time after a crash occurs, CRT is an important independent variable in the model. An ordered logistic regression (OLR) is used for the modeling. Odds ratios for each independent variable can be used to estimate the percentage change in injury severity when a variable changes by one unit. In addition, the probabilities of injury severity can be calculated for with and without the ACNS. The second step is to estimate the average CRT 'with and without ACNS'. A functional form with components that impact CRT is constructed to estimate the average CRT. These components include the market penetration rate (MPR) and the reduction in CRT with the ACNS. A probability density function for CRT is derived and used for estimating a range of CRTs based on a given confidence interval. Next, the range of CRTs from Step 2 is applied to the injury severity prediction model in Step 1 to estimate the changes in the probabilities of injury severity in Step 3. Once we have the changes in injury severity, the total number of crash victims to who will be saved or less injured can be calculated. More detailed descriptions for each step are presented in the following subsections.

[Step1] Identifying the Effect of CRT on Injury Severity

This study develops a statistical model that predicts injury severity of crash victims. The model is used to identify the effect of CRT on injury severity. Because crash injury severity is intrinsically ordered, the model must account for ordinal characteristics. For this reason, an ordered logistic regression technique is appropriate The ordered model can be specified as $y_i^* = \beta' x_i + \varepsilon_i$, where y_i^* represents the injury severity of the crash victim and x_i represents the independent variables that affect injury severity. These independent variables include vehicle characteristics, roadway geometric conditions, response activities to the crash, and environmental conditions. This study classifies injury severity into three levels: fatality, severe injury, and slight injury. Next, threshold values (μ) are used to categorize the levels of severity as follows:

$$
\begin{aligned}
y_i(\text{severity}) &= 1,\ \text{'fatality'}, && \text{if } y^* \le \mu_1 \\
y_i(\text{severity}) &= 2,\ \text{'severe injury'}, && \text{if } y^* \le \mu_2 \\
y_i(\text{severity}) &= 3,\ \text{'slight injury'}, && \text{if } y^* \le \mu_3
\end{aligned}
$$

The maximum likelihood estimation method is used to calibrate the parameters:

$$
L(y|\beta;\ \mu_1, \mu_2, \mu_3) = \prod_{i=1}^{n} \prod_{j=1}^{3} \left[\gamma(\mu_j - \beta' x_i) - \gamma(\mu_{j-1} - \beta' x_i)\right]^{Z_{ij}},
$$

where

γ_j: cumulative probability,
$\gamma_j(x_i) = \gamma_j(\mu_j - \beta' x_i) = P(y_i \le j|x_i)$,
β: parameter to be calibrated, and
$Z_{ij} = 1$, if the observed category for the individual i is j, and 0 otherwise.

In addition, the probability that the injury severity y with the independent variable x_k is less than j is estimated using Eq. (1). More detailed information on ordered logit models and the relevant derivations can be found in the literature *(17-18)*. The odds ratio for x_k, which is expressed as e^{β_k}, is used to quantify the changes in the probabilities of injury severity when x_k changes by one unit. In this application, CRT becomes a key independent variable that affects the injury severity.

$$
\Pr(y \le j|x) = \frac{e^{\mu_j - \sum_{k=1}^{K} \beta_k x_k}}{1 + e^{\mu_j - \sum_{k=1}^{K} \beta_k x_k}} \qquad (1)
$$

[Step2] Estimation of the Average Reduced Crash Response Time (CRT)

In this step, the average CRT is estimated with the assumption that the ACNS has been implemented with a given market penetration rate (MPR). Therefore, factors that affect the average CRT include the MPR and the reduction in CNT (ΔCNT) with the ACNS. The average CRT with the ACNS and a given MPR is expressed in Eq. (2).

$$
\begin{aligned}
CRT_{ACINS} = &\left(CRT_{ACINS}^{No}\right)(1 - MPR_{ACINS}) + \\
&\left(CRT_{ACINS}^{No} - \Delta CNT\right)(MPR_{ACINS}) \qquad (2)
\end{aligned}
$$

where

CRT_{ACNS}: average reduced CRT (min) with the ACNS,
CRT_{ACNS}^{No}: observed CRT (min) from the existing freeway crash database without the ACNS,
MPR_{ACNS}: market penetration rate (%) of the ACNS, and
ΔCNT: reduced CNT (min) with the ACNS (min)

The first term in Eq. (2) represents CRT for vehicles that are not equipped with an ACNS, and the second term represents CRT for ACNS-equipped vehicles. An important issue is to determine whether CRT_{ACNS}^{No} and ΔCNT in Eq. (2) are treated as parameters or constants in estimating

CRT_{ACNS}. In this study, CRT_{ACNS}^{No} is regarded as a parameter that varies, as there are unknown factors that affect CRT in practice, including traffic conditions, the availability of EMS, and the crash severity. An approach for treating CRT_{ACNS}^{No} as a parameter is to determine a statistically significant probability density function (PDF) with actual data from freeway crashes. Random sampling of $CRTs_{ACNS}^{No}$ from the derived PDF can then be repetitively conducted to generate a set of $CRTs_{ACNS}^{No}$, and the $CRTs_{ACNS}^{No}$ can be used to estimate CRT_{ACNS}. A set of MPRs is applied to estimate CRT_{ACNS}, because a 100% MPR is unlikely and would not be obtainable in a short time period. On the contrary, ΔCNT can be regarded as a constant, which depends on the technology; CNT varies less than CRT, as CRT depends on uncontrollable factors. In this application, we adopted the results from the National Highway Safety Administration (NHTSA) field operational test (FOT) *(19)*. The NHTSA reported that most CNTs for ACNS-equipped vehicles were less than 1 min. However, the average CNT for vehicles that are not equipped with the ACNS was 5.6min. In this study, 4.6 min was used for ΔCNT, which conservatively assumes that the average CNT for ACNS-equipped vehicles is 1 min.

[Step3] Assessments of the Safety Benefits of the ACNS

The changes in the probabilities of crash injury severity with reduced CRTs are used to obtain the safety benefit. For example, as shown in Figure 3, the reduced changes in the probabilities for fatality and severe injury are regarded as safety benefits. Meanwhile, the probability of minor injury increases, as the function of the ACNS is to alleviate crash severity rather than to prevent crashes from occurring. That is, the total number of crashes does not change when the ACNS is applied. This study focuses on fatality and severe injury in estimating the safety benefits of the ACNS.

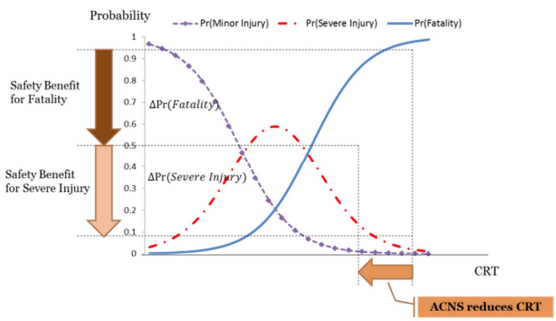

Figure3. Conceptual illustration of obtainable safety benefits by ACNS

An approach to quantifying the safety benefits of the ACNS is to determine the reductions in the number of fatalities and severe injuries. Because the ACNS can reduce CRT, the changes in the probabilities of injury severity can be computed with Eq. (1). Assuming that other independent variables (X_i) would not vary, the reduction in the percentage of fatality and severe injury can be expressed as Eq. (3) and Eq. (4). In addition, the reduced number of fatalities and severe injuries can be expressed as Eq. (5) and Eq. (6):

$$Eff_{Fatal} = Pr(Fatality|CRT_{ACNS}^{No}, X_i) - Pr(Fatality|CRT_{ACNS}, X_i) \quad (3)$$

$$Eff_{Severe} = Pr(Severity\ Injury|CRT_{ACNS}^{No}, X_i) - Pr(Severity\ Injury|CRT_{ACNS}, X_i) \quad (4)$$

$$\Delta NF = NF_{ACNS}^{No} \times Eff_{Fatal} \quad (5)$$

$$\Delta NS = NS_{ACNS}^{No} \times Eff_{Severe} \quad (6)$$

where

Eff_{Fatal} : fatality reduction percentage with the ACNS,
Eff_{Severe}: severe injury reduction percentage with the ACNS,
$Pr(Fatality|CRT_{ACNS}^{No}, X_i)$: probability of fatality without ACNS,
$Pr(Severe|CRT_{ACNS}^{No}, X_i)$: probability of severe injury without the ACNS,
$Pr(Fatality|CRT_{ACNS}, X_i)$: probability of fatality with the ACNS,
$Pr(Severe|CRT_{ACNS}, X_i)$: probability of severe injury with the ACNS,
ΔNF: reduced number of fatalities with the ACNS,
ΔNS: reduced number of severe injuries with the ACNS,
NF_{ACNS}^{No}: number of fatalities without the ACNS,
NS_{ACNS}^{No} : number of severe injuries without the ACNS.

DATA

This study used freeway crash data from Korean freeways. As of 2010, the Korean freeway systems consist of 32 freeway lines with a total of 3,859km of freeway. In 2010, approximately 1,377,062,000 vehicles traveled freeways. The most recent three years of crash data, 2008-2010, were used in this study. During that time, 11,282 crashes occurred on Korean freeways, and there were 1,195 fatalities and 28,663 injuries. The Korea expressway corporation (KEC) is in charge of construction, maintenance, and traffic operations for Korean freeways. Crash management teams under the KEC collect crash-related data including crash severity, occurrence time, location, crash types and causes,

geometric conditions, traffic conditions, driver's characteristics, and weather conditions. The Korean freeway crash database is updated whenever a crash occurs. The database also has valuable information on crash response and clearance, which includes crash duration, clearance time, and arrival time of emergency medical service. In this study, we defined the time difference between crash occurrence time and arrival time of emergency medical service as CRT.

AN APPLICATION OF PROPOSED METHODLOGY

A set of candidate factors that affect crash injury severity were extracted from the database. These factors include driver characteristics, geometric conditions, weather conditions, vehicle types, and crash response times. Table 1 presents the variables that were used in this study for developing a statistical model to predict crash injury severity. CRT was a continuous variable in minutes, but other variables were treated as nominal and discrete.

Table1. Variable descriptions

Variable		Descriptions
Dependent Variable	Injury severity	Fatality (2), Severe injury (1), Minor injury (0)
Independent Variable	Weather (X_1)	Clean/cloudy (0), Others (1)
	Daytime/nighttime (X_2)	Daytime (0), Nighttime(1)
	Horizontal alignment (X_3)	Tangent (0), Curve (1)
	Vertical alignment (X_4)	Level (0), Grade(1)
	Lighting (X_5)	Yes (0), No (1)
	Vehicle type (X_6)	Passenger car (0), Others (1)
	Driver gender (X_7)	Male (0), Female (1)
	CRT (X_8)	Continuous (min)

The statistical software package program SPSS was used to predict injury severity. The results of the model development are summarized in Table 2. The value of Chi-square for the logistic regression model is 886.231. Among the eight candidate variables, but excluding weather (X_1), horizontal alignment (X_3) and gender (X_7), five variables were identified as statistically significant using Wald-statistic tests. The signs of the coefficients of the independent variables for daytime/nighttime (X_2), lighting (X_5), and CRT (X_8) are positive. On the contrary, horizontal alignment (X_3) and driver gender (X_7) had negative coefficients. These results imply that the injury severity increases when a crash occurs at nighttime and without lighting, with larger and longer CRTs, and when a male driver is involved. The probability model with the estimated coefficients is shown in Eq. (7-9).

Table2. Regression modeling results

Para-meter	β	Wald statistic	Significance probability	Odds ratio $\exp(-\beta)$
μ_1	0.855	43.94	0.000	-
μ_2	1.308	99.05	0.000	-
X_2	0.641	38.78	0.000	0.527
X_3	-0.395	13.69	0.000	1.484
X_5	0.636	28.91	0.000	0.529
X_7	-0.463	7.14	0.008	1.589
X_8	0.101	182.17	0.000	0.904

• MFI Chi-square: 886.231 (MFI sig.: 0.000)
• -2 log likelihood: 1209.974
• Nagellerke R-square: 0.212

$$Pr(Minor|X) = \frac{\exp(\mu_1 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)}{1 + \exp(\mu_1 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)} \quad (7)$$

$$Pr(Severe|X) = \frac{\exp(\mu_2 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)}{1 + \exp(\mu_2 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)} - \frac{\exp(\mu_1 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)}{1 + \exp(\mu_1 + \beta_2X_2 + \beta_3X_3 + \beta_5X_5 + \beta_7X_7 + \beta_8X_8)} \quad (8)$$

$$Pr(Fatality|X) = 1 - Pr(Minor|X) - Pr(Severe|X) \quad (9)$$

To estimate the $\mathrm{CRT_{ACNS}}$ (refer to Eq. (2)) that will be used in the injury prediction models in Eq. (7-9). 7,189 observed CRTs were analyzed from the crash database ($\mathrm{CRT^{No}_{ACNS}}$). The average and median of $\mathrm{CRTs^{No}_{ACNS}}$ are 11.00 and 10.00, respectively. The first task for estimating $\mathrm{CRT_{ACNS}}$ is to derive an appropriate PDF for $\mathrm{CRT^{No}_{ACNS}}$. A variety of probability density functions were fitted to the $\mathrm{CRT^{No}_{ACNS}}$ data. In this study, a normal density function ($N(\mu = 11, \sigma^2 = 7.39)$), which shows the smallest error value, was selected for the $\mathrm{CRT^{No}_{ACNS}}$ distribution function.

Next, normally distributed random $\mathrm{CRTs^{No}_{ACNS}}$ were extracted from the estimated normal PDF. A constant value of ΔCNT 4.6-min and the given MPRs ranging from 10 to 100% were applied to Eq. (2). A set of $\mathrm{CRTs_{ACNS}}$ was then established. In this case, an estimation of the CRT ($\widehat{\mathrm{CRT}}_{\mathrm{ACNS}}$) interval for a given MPR can be expressed as Eq. (10).

$$\overline{\mathrm{CRT}}_{\mathrm{ACINS}} - I \le \widehat{CRT}_{\mathrm{ACINS}} \le \overline{\mathrm{CRT}}_{\mathrm{ACINS}} + \mathrm{I} \quad (10)$$

where

$$\mathrm{I} = \frac{t_{\frac{\alpha}{2},8}\sigma_{\mathrm{CRT_{ACINS}}}}{\sqrt{n}}$$

$\overline{CRT}_{ACNS}$: average CRT_{ACNS},
$\widehat{CRT}_{ACNS}$: interval estimation of CRT_{ACNS},

$t_{\frac{\alpha}{2},\vartheta}$: t-statistic with degrees of freedom ϑ and significance probability α,
$\sigma_{CRT_{ACNS}}$: standard deviation of CRT_{ACNS}, and
n: number of samples.

To estimate the safety benefits, the probabilities of injury severity are estimated with and without the ACNS. The CRTs that were derived from the above method are applied to Eq. (7-9) for minor injury, severe injury and fatality, respectively. The number of reduced fatalities and severe injuries can then be obtained using Eq. (5) and (6). As an application of the proposed methodology, the results of the estimated safety benefits of the ACNS, using 2010 crash data, are presented in Figure 4, 5. The total number of fatalities in 2010 is 389. Among them, approximately, 70 fatalities would be saved with a 100% MPR for the ACNS, which represents an 18.07% reduction in fatalities. Furthermore, up to 42 severely injured crash victims would be less injured with a 100% MPR, which represents a 1.49% reduction in severe injury. The relatively small reduction in severe injury can be explained by the fact that the injuries can either be severe injuries, fatalities, or minor injuries.

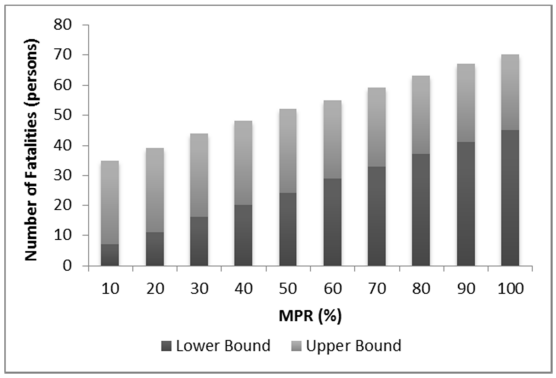

Figure4. Reduced number of fatalities with ACNS

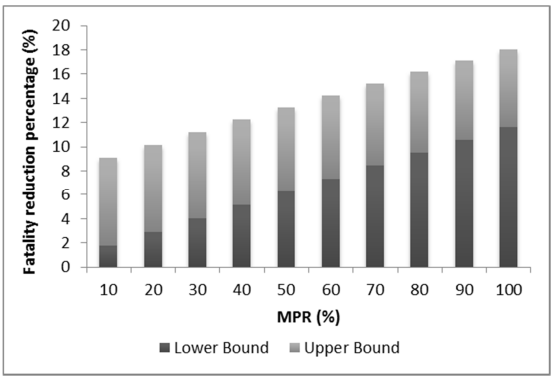

Figure5. Fatality reduction percentage with ACNS

CONCLUSION

Substantial efforts have been made to enhance traffic safety on the road. These efforts can be comprehensively classified into two groups: preventing crashes and reducing injury severity. Preventing crashes is the preferred approach to enhance safety and to establish a crash-free transportation system. However, intricately related causal factors affect the occurrence of crashes. These complex causal relationships do not allow for the complete crash prevention. Therefore, reducing injury severity is an effective countermeasure after crashes occur.

A variety of technical countermeasures that can reduce injury severity have been widely developed in support of recent sensor and communication technologies. One promising countermeasure is the ACNS, which can reduce crash response time and provides additional opportunities to save the lives of crash victims. An important issue to fully utilize the ACNS is to quantify the safety benefits, which is fundamental for justifying the public investment. This study proposed a methodology for quantifying the safety benefits of the ACNS and applied the methodology to the Korean freeway systems.

The proposed methodology to estimate the safety benefits of ACNS consists of three steps. First, an injury severity prediction model based on OLR was developed. Various contributing factors, such as geometric conditions, weather conditions, and CRT, were used as independent variables in the model. Three levels of injury severity, including fatality, severe injury, and minor injury, can be predicted as probabilistic outcomes according to changes in the independent variables. The modeling result showed that following variables were statistically significant: daytime/nighttime, horizontal alignment, lighting, driver gender, and CRT. Second, $\mathrm{CRT_{ACNS}}$ was estimated using $\mathrm{CRT_{ACNS}^{No}}$, and ΔCNT was obtained with the ACNS at a given MPR. A nice feature was that a PDF for $\mathrm{CRT_{ACNS}^{No}}$ was derived with density function analyses, and used to generate a set of $\mathrm{CRTs_{ACNS}}$ to consider their variability. Afterward, various $\mathrm{CRT_{ACNS}}$ values were used as inputs to the injury prediction model to estimate the probabilities of injury severity. Then, the numbers of reduced fatalities and severe injuries were quantified. The reduction of CRT ranged from 4.85 min to 7.89 min in the case of a 100% MPR for the ACNS. This change would eliminate 70 fatalities and 42 severe injuries in the crash data from 2010.

A significant contribution of this research is to present a methodology for quantifying and analyzing the effectiveness of the ACNS in existing data. Nevertheless, further exploration is required to develop injury prediction models and to estimate $\mathrm{CRT_{ACNS}}$. Variables that represent traffic conditions,

such as speed or travel times, can be used as independent variables, as they impact CRT variability. Additionally, in addition to OLR, other modeling techniques would improve the statistical significance. Finally, crash data collected from signalized arterials and intersections should be analyzed.

The proposed methodology provides valuable insight into the development of methodology for evaluating other countermeasures that can reduce injury severity. In addition, the outcomes of this study support decision making for public investments and for establishing relevant traffic safety policies.

ACKNOWLEDGEMENT

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