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Predicted effect of automatic crash notification on traffic mortality

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Abstract

Objective: To estimate the reduction in traffic mortality in the United States that would result from an automatic crash notification (ACN) system. *Methods*: 1997 Fatality Analysis Reporting System (FARS) data from 30875 cases of incapacitating or fatal injury with complete information on emergency medical services (EMS) notification and arrival times were analyzed considering cases at any time to be in one of four states: (1) alive prior to notification; (2) alive after notification; (3) alive after EMS arrival; and (4) dead. For each minute after the crash, transition probabilities were calculated for each possible change of state. These data were used to construct models with (1) number of incapacitating injuries ranging from FARS cases up to an estimated total for the US in 1997; (2) deaths equal to FARS total; (3) transitions to death from other states proportional to FARS totals and rates and (4) other state transitions equal to FARS rates. The outcomes from these models were compared to outcomes from otherwise identical models in which all notification times were set to 1 min. *Results*: FARS data estimated 12 823 deaths prior to notification, 1800 after notification, and 14 015 between EMS arrival and 6 h. If notification times were all set to 1 min, a model using FARS data only predicted 10 703 deaths prior to notification, 2306 after notification, and 15 208 after EMS arrival, while a model using an estimated total number of incapacitating injuries for the US predicted 9569 deaths prior to notification, 2261 after notification, and 15 134 after arrival. In the first model, overall mortality was reduced from 28 638 to 28 217 (421 per year, or 1.5%), while in the second model mortality was reduced to 26964 (1674 per year, or 6%). *Conclusions*: Modest but important reduction in traffic mortality should be expected from a fully functional ACN system. Imperfect systems would be less effective.

Keywords: Automatic crash notification; Motor vehicle; Mortality; FARS

1. Introduction

Victims of serious injury are obviously more likely to die if their medical treatment is delayed. However, the rate at which this risk increases with time is not so obvious, nor is the effect of medical intervention at various times after injury. Establishing these quantities may have important implications for injury epidemiology and for the assessment of interventions to reduce mortality after an injury has occurred.

A specific intervention of interest is automatic crash notification (ACN), whereby vehicle crash sensors and geographic locator systems could immediately notify the emergency medical services (EMS) system when and where a life-threatening crash has occurred. Devices of this sort have already been installed in some vehicles, and local pilot projects linking them to a system of communication and dispatch are currently in progress (Champion and Cushing, 1999). The purpose of this study was to use existing data from fatal crashes to estimate the effect of EMS notification and arrival on survival times, and to use these estimates to predict the effect of a fully functional ACN system on traffic mortality in the United States.

2. Methods

Data on vehicle crashes for 1997 in the Fatality Analysis Reporting System (FARS) were obtained from the National Highway Traffic Safety Administration

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(NHTSA) on a compact disc along with a Coding and Validation Manual (USDOT, 1997). Cases are included in FARS if at least one fatality occurs within 30 days as the result of a vehicle collision on a public road (USDOT, 1998). The data are presented in four tables relating to the event (Level 1), each vehicle involved (Level 2), each driver involved (Level 3), and each person involved (Level 4, including survivors as well as decedents). Selected data from each of these levels were imported into a relational database table using Access (Microsoft, Redmond WA).

From the person-level data, persons designated as drivers or passengers in a motor vehicle in transport were selected along with other data including whether they were hospitalized, their severity of injury (including death) as reported by police, and the time from injury until death if they died. Using common data elements (state and crash number) for linkage, collision-level data were added, including the county where the collision occurred, time of collision, time of EMS notification, and time of EMS arrival at the scene. County population and area obtained from the U.S. Census (USDOC, 1996) were linked to the FARS data and used to analyze the results by county population density.

Cases were excluded if their injuries had not been reported by police as either fatal or incapacitating. Cases were excluded if crash time or EMS arrival time was missing (including cases for which the hour was present but the minute was missing). Fatal cases were excluded if the time lag from injury to death was missing or reported as a negative number.

Lag times from injury to EMS arrival were calculated using the necessary modular arithmetic. Records with prolonged EMS arrival times were carefully inspected: Cases not recorded as immediate fatalities which had calculated lag times greater than 10 h were excluded, since the majority of these appeared to have resulted from coding errors related to 24-h clock time (e.g., 4:00 P.M. recorded as 0400 or 1400). Likewise, cases that had calculated lag times less than zero, and cases recorded as hospitalized but not transported by EMS were excluded.

After preliminary analyses, cases were further excluded if the time at which EMS had been notified was missing (including cases where the hour was known but the minutes were missing), or if the time of EMS notification was recorded as being before the time of the crash or after the arrival of EMS.

Data were imported into Mathematica (Version 3.0, Wolfram Research, Champaign, IL) for programming and graphical presentation. For each minute from the time of crash until 6 h, each case was determined to be in one of four states, namely:

1. Alive, with EMS not yet notified
2. Alive, with EMS notified but not yet arrived
3. Alive, after EMS arrival, or
4. Dead.

For each minute, the probability that an individual in one state would move to another state was then calculated from the data, that is

$$h_{xy}(t) = \frac{\text{cases moving from state } x \text{ to state } y \text{ in minute } t}{\text{cases in state } x \text{ at start of minute } t}$$

We will refer to these instantaneous probabilities as 'hazards', and for each possible transition, we will refer to the rule that associates a hazard for each minute after the crash as the 'hazard function' for that transition.

Using the hazard functions calculated from FARS data, a computer model was constructed (Fig. 1), which was validated by producing the same results as the original data when the same number of cases was initialized as alive without EMS notification at time zero. Because FARS only includes subjects from crashes in which a fatality occurred, a realistic model must consider persons at similar risk in crashes where no fatality occurred. Therefore, the model was also evaluated after multiplying each of the three hazard functions resulting in death by an appropriate factor such that when the estimated total number of incapacitating or fatal injuries for drivers and passengers in the United States in 1997 (derived from the General Estimates System (USDOT, 1998, page 86)) was initialized at time 0, the number of deaths remained the same as in the original data derived from FARS and occurred in the same proportions from each of the alive states. The hazard functions for moving from one alive state to another in the model were kept the same as those derived from FARS.

To assess the potential influence of ACN, the hazard for moving between the state 'alive with EMS not yet

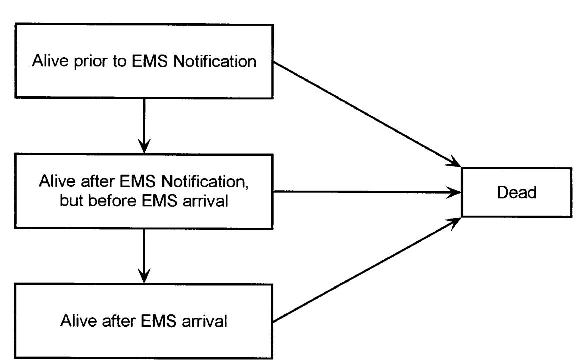

Fig. 1. Multi-state model used for analysis.

Table 1
Characteristics of FARS cases with sufficient data to include in model construction and those excluded because of missing data

	Included ($n = 30\,875$)	Excluded ($n = 21\,429$)
County population density		
<16/square mile	2985 (9.7%)	909 (4.2%)
16–40 / square mile	4901 (15.9%)	2088 (9.7%)
40–99 / square mile	6800 (22.0%)	4707 (22.0%)
> 99 / square mile	16,189 (52.4%)	13,725 (64.1%)
Drivers	18,799 (60.9%)	13,237 (61.8%)
Hospitalized	20,254 (65.6%)	14,111 (65.9%)
Died	20,490 (66.4%)	14,892 (69.5%)

notified' to 'alive with EMS notified but not yet arrived' in the first minute was set to 1 for all individuals who did not die in that first minute. Thus, all survivors were in the latter state by the second minute, as if an ACN system had immediately notified EMS of the crash. The outcomes of the models after this single additional modification were compared with the outcomes of the models before this modification.

Hazard functions for moving from each alive state to death were also analyzed and compared graphically.

3. Results

There were 35,382 vehicle drivers and passengers in FARS who died, and 16,922 others who had incapacitating injuries. Of these 52,304 cases, only 30,875 had complete data allowing calculations for the models; the most frequent missing data were specific EMS notification and/or arrival times. Some differences between the cases included and excluded are given in Table 1. Complete data were less likely to be present in more urban counties, but otherwise the cases used for model construction were similar to those excluded due to missing data.

The hazard for death following a vehicle collision among FARS patients was highest immediately after the event, with 37% of FARS deaths reported as instantaneous (0–1 min). Thereafter, survival declined more gradually. Of the cases with fatal or incapacitating injuries, half had died by 110 min. For half of surviving cases, EMS had been notified by 4 min and had arrived by 13 min. The model based upon FARS data alone (multiplied by 52,304 / 30,875 to correct for cases missing data) reproduced these findings accurately (Fig. 2).

When the model was expanded to include the estimated 387,000 additional cases of incapacitating injury

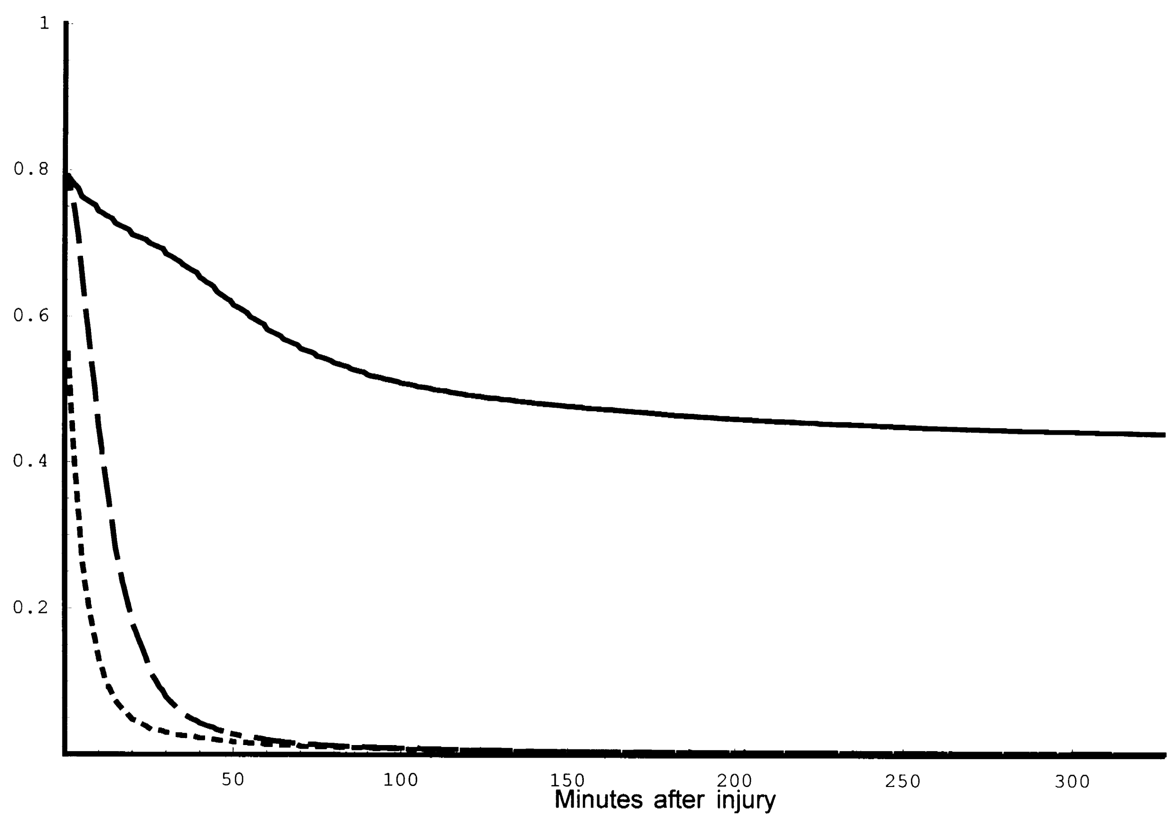

Fig. 2. Analysis for 1997 FARS cases of fatal or incapacitating automobile injury with complete data. Solid line represents proportion surviving, long dashed line represents proportion alive awaiting EMS arrival, and short dashed line represents proportion alive awaiting EMS notification.

Table 2
Model results predicted for mortality with and without ACN

	Predicted deaths within 6 h of injury		
	Without ACN	With ACN	
		FARS Data	FARS/GES Data
Prior to EMS notification	12 823	10 703	9569
After notification, but prior to EMS arrival	1800	2306	2261
After EMS arrival	14 015	15 208	15 134
Total	28 638	28 217	26 964

The overall difference is 421 fewer deaths with ACN if only FARS data are used, and 1674 fewer deaths with ACN if FARS and General Estimates System (GES) estimates are used to construct the model.

not included in FARS, the proportion surviving was correspondingly much greater, with 94% of cases still alive at 110 min. However, for half of surviving cases in the model, EMS had still been notified by 4 min and had arrived by 13 min. The hazard ratios by which calculated FARS rates were multiplied to obtain the same numbers of deaths for each fatal transition were 0.10791 for the transition from 'EMS not notified', 0.09205 for the transition from 'EMS notified but not yet arrived', and 0.07368 for the transition from 'EMS arrived'. When the transition time for 'EMS not notified' to 'EMS notified but not yet arrived' was set to 1 min for all cases, the number of fatalities changed as shown in Table 2. The decreased number of deaths occurring prior to EMS notification more than offset the increase occurring after EMS notification, with an overall outcome of 421 fewer deaths if only FARS data were considered, or 1676 fewer deaths if the total number of GES and FARS cases of fatal or incapacitating injury were considered.

Analysis of the transition rates from each alive state to death (equivalent to standard Kaplan–Meier graphs with other transitions censored), showed relatively smooth curves (except for the initial sharp drop) with decreasing hazards for cases in which EMS had not been notified and for those after EMS arrival. For cases in which EMS had been notified but had not yet arrived, survival was similar to those after EMS arrival, but had interesting deviations from this curve between the 45th and 90th minutes and after 180 min (Fig. 3). Hazard rates were very high in the first minute, and then decreased for all groups for the next several hours; although data quality for those victims apparently still not attended by EMS after several hours is questionable, the hazard appeared to increase.

4. Discussion

The increased mortality rate for injuries in rural areas has been recognized, and great efforts are being made to improve medical services, emergency transportation, and communication in rural areas (Rogers et al., 1999). Unfortunately, geographical constraints themselves may explain much of the increased mortality in areas of low population density (Clark and Cushing, 1999), and provision of specialized surgical services in sparsely settled areas may be impractical. Rapid air transportation of seriously injured patients to trauma centers is a partial solution, but still limited by physical and economic realities. While education and organization of EMS services can always be improved, the most promising opportunity for cost-effective improvement is to utilize new technology for inexpensive, instantaneous communication of medical expertise, resource availability, and patient requirements (Brodsky and Hakkert, 1983).

ACN systems use computer and telecommunications technologies to alert the EMS system automatically when crashes activate an airbag, cause certain decelerations or deformations in the vehicle, or are activated by an occupant of the vehicle (Brodsky and Hakkert, 1983; Champion and Cushing, 1999). Such systems are already available in some vehicles, and provide the potential opportunity to reduce delays in the activation of the EMS system by ensuring that the occurrence of a serious vehicle crash will be reported. Anecdotal reports of disabled victims of crashes in remote areas unreported to EMS exist, but the frequency with which such situations arise is unknown.

Evanco (1999) constructed a regression model using various characteristics of the individual states of the U.S.A., including average EMS notification time (obtained from FARS), and concluded that a perfect ACN system in rural areas could reduce vehicle related mortality by 3069/year. While such ecological studies are suggestive, the analysis of data averaged by region (especially when the regions vary greatly in size) is susceptible to numerous kinds of error (Rothman, 1986). We believe that a study such as ours, based upon individual cases, may have additional value.

FARS data have been diligently collected for more than 20 years, and have proven their worth in the analysis of potential vehicle modifications or legal measures to prevent fatal crashes. They have been used less in the analysis of EMS systems, partly because of incomplete or unreliable data. For example, times are often rounded to the nearest 5 min (Brodsky, 1993), and we found numerous discrepancies in recorded times as described under our methods and results. There were many victims 'killed instantly' given a survival time of 0, whose time of death could not actually have been witnessed by police or EMS providers who arrived later. These concerns also are among the limitations of our study, although it seems likely that the model outcomes would have been similar even if complete data had been available for all FARS cases (Table 1).

We would have liked to have used the time of arrival at a hospital as a covariate, but unfortunately FARS records only the time of arrival at a hospital for 'the unit transporting the most severely injured victim', if that person does not die at the scene, or 'the first victim to arrive' if there is more than one with comparable severity (USDOT, 1997). It is therefore generally impossible to determine a case-specific time of arrival at the hospital. We made the assumption that the effect of EMS arrival on the scene would be applied to all victims of the same collision. The direct effect of pre-hospital EMS intervention in traumatic cases is limited (Sampalis et al., 1993), but at least communication and transport in the direction of a hospital can be initiated once an ambulance has arrived. We believe that most of the effect of EMS demonstrated in our model can in fact be attributed to arrival of the patient at a hospital soon afterward.

We limited our analysis to fatal cases and those classified by police as having 'incapacitating injury', reasoning that cases at risk for death would only be in these groups. We assumed that this would especially be true of cases not hospitalized, and in fact essentially all FARS survivors with incapacitating injury were hospitalized or transported by EMS in less than 6 h. Brodsky and Hakkert (1983) used similar reasoning to study the ratio of cases with 'incapacitating injury' to fatal cases in Texas counties with different population densities, and showed that this ratio was lower in the more remote counties. Our model is sensitive to the number of subjects initialized at risk for mortality. Surely this number is substantially larger than the cases included in FARS, but it seems unlikely to be larger than the total number of crash victims judged to have 'incapacitating injury' by police. We have therefore used these extremes to define a range of outcomes that might be expected to include a 'correct' prediction of lives saved by an ideal ACN system.

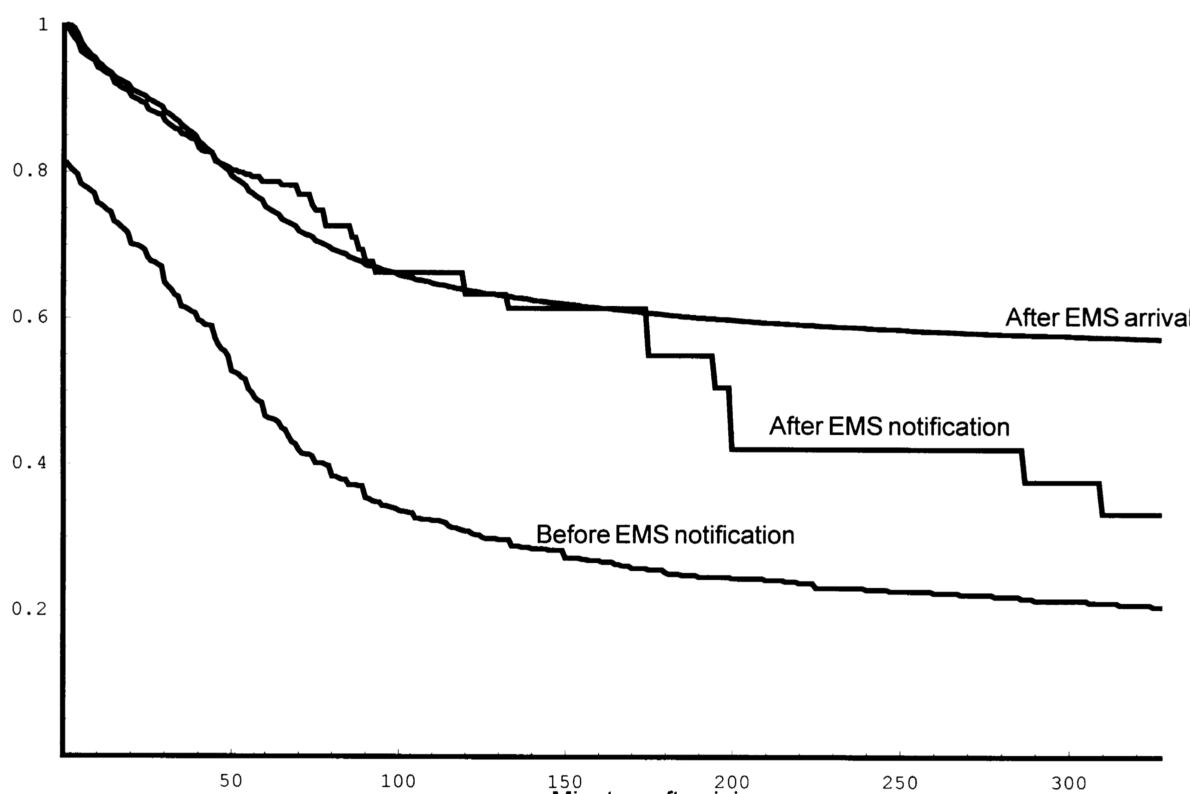

Fig. 3. Kaplan–Meier survival estimates for cases in three alive states.

ACN would be unlikely to affect the large proportion of traffic deaths occurring within a few minutes of impact. Many others have noted the rapid decline in survival immediately after injury, followed by a gradual decrease in the rate of change. Several studies considered cumulative mortality as a linear function of the logarithm of time (Robertson and Tonge, 1968; Sevitt, 1973; Tsuchihashi, 1983), but Hutchinson (1974) pointed out that this would predict greater than 100% mortality for large values of t, and proposed instead using the model

$$S(t) = \exp(-a\ t \wedge p),$$

where a and p are constants and $S(t)$ is the proportion surviving at time t. This mathematical relationship is generally known as a Weibull function, named after the Swedish engineer who used it to study reliability of materials (Collett, 1994; Stata, 1995). Weibull functions are appropriate if the hazard steadily increases ($P > 1$) or decreases ($P < 1$) over time; an exponential function is a special case of a Weibull function where $P = 1$, in which case the hazard remains constant.

Although it has been stated that the frequency of deaths after injury follows a 'trimodal distribution', the second and third peaks in these graphical descriptions (Trunkey, 1983; Sauaia et al., 1995; Meislin et al., 1997) are produced or at least greatly exaggerated by changes in the time scale. Other artifacts which may lead to the impression of subsequent peaks include reporting data only from hospitals to which the most serious cases have been transferred, arbitrary timing of the declaration of brain death, and rounding errors when the actual times of injury and/or death are unknown. The 'trimodal distribution' may be a useful pedagogical idea (ACS 1997), but should not be considered a proven biological fact. The apparent transient rise in the hazard at about 45 min in FARS data, previously noted by Luchter et al. (1998), appeared in our analysis only among cases after EMS notification but prior to EMS arrival (Fig. 3), and may also be an artifact resulting from recognition of death at the time of EMS arrival.

Observers in many parts of the world have consistently noted an increased mortality rate from traffic injuries in less populated areas (Brodsky and Hakkert, 1983; Baker et al., 1987; Tsuchihashi, 1983; Yang et al., 1997; Clark et al., 2000). We are not aware of any previous research considering separately survival with and without medical intervention. Due to the uncertainties about exact data, it is difficult to determine a functional form for the survival curves, but the decreasing hazard in the early period after a crash, with or without EMS intervention, is generally consistent with a Weibull survival model. We have shown elsewhere (Clark and Cushing, 1999) that assumption of a Weibull model for the first few hours after injury leads to the approximately inverse linear relationship between the logarithm of the traffic mortality rate and the logarithm of the population density that has been observed. The current study provides additional evidence that regional variation in the time required to initiate effective treatment is an important determinant of regional variations in injury mortality rates.

For crash victims who enter the medical care system, the hazard continues to fall and a Weibull model may be useful to predict survival even over several weeks (Hutchinson, 1974). For crash victims still not attended by EMS after about 6 h, the hazard may actually rise, and a Weibull model would no longer be appropriate. It is possible that this impression from the FARS data is partly an artifact resulting from improper data entry, but also biologically plausible that crash victims with incapacitating injury who survive their initial injury but are still not discovered and transported to a hospital would become increasingly likely to die. Few such victims remain unattended for many hours, but these are clearly the ones who would benefit most from ACN.

Our model makes the assumption that the effect of ACN would be limited to the risk of death within 6 h of injury. It is conceivable that earlier medical attention would also reduce late deaths, but it would be difficult to build this into a mathematical model. We also did not attempt to model the possibility that EMS arrival time after notification might be quicker due to better information about location or specific injuries as the result of an ACN system. Since our data are based upon FARS, we also cannot estimate the reduction in mortality occurring on non-public roads, and are limited by the data quality issues described earlier.

Despite these and other limitations, it appears from our model that an ideal ACN system would result in somewhere between 421 and 1676 fewer deaths from traffic crashes each year in the United States, or about 1.5% to 6% of the annual total. This estimate is somewhat lower than the predictions of Evanco (1999). Both that study and ours suggest that ACN would be most useful in rural areas, where EMS notification and arrival times are longer. Speculation about the potential contributions of ACN to rural trauma system development other than the direct effect of earlier EMS notification is beyond the scope of this study.

Some of the same benefit may result from the more widespread use of portable telephones, although a totally automatic system would be particularly valuable for areas without telephone coverage or when nobody at the scene is capable of dialing a telephone. ACN or similar systems may also be useful for other persons with medical emergencies, such as elderly people living alone, inhabitants of very remote areas, and those engaged in outdoor recreational activities. The technology has become relatively inexpensive, may be combined with other functions or services, and deserves further evaluation.

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