

OCCUPANT TRANSPORTATION DECISION ALGORITHM: AN ADVANCED AUTOMATIC CRASH NOTIFICATION ALGORITHM DEVELOPED AND EVALUATED FOR MOTOR VEHICLE CRASH OCCUPANT TRIAGE

Joel Stitzel, Ashley Weaver, Samantha Schoell

Virginia Tech-Wake Forest Center for Injury Biomechanics
United States

Ryan Barnard, Jennifer Talton, R. Shayn Martin, J. Wayne Meredith

Wake Forest School of Medicine
United States

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ABSTRACT

The objective was to develop an Advanced Automatic Crash Notification (AACN) algorithm and evaluate its performance in making optimal occupant triage decisions. The developed AACN algorithm known as the Occupant Transportation Decision Algorithm (OTDA) uses measurements obtainable from vehicle telemetry to predict risk of overall occupant injury and recommend a transportation decision for the occupant following a motor vehicle crash (MVC), particularly whether transport to a Level I/II trauma center is recommended. A list of injuries necessitating treatment at a Level I/II trauma center (TC) was determined using an injury-based approach based on three facets (severity, time sensitivity, and predictability). These three facets were quantified for each injury from expert physician and emergency medical services (EMS) professional opinion and database analyses of the National Trauma Data Bank and National Inpatient Sample. Severity, Time Sensitivity, and Predictability Scores were summed for each injury to compute an Injury Score. Injuries with an Injury Score exceeding a particular threshold were included on the Master Target Injury List, which is a list of injuries more likely to require Level I/II TC treatment. OTDA inputs for development include the Master Target Injury List and 38,970 National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) 2000-2011 occupants. The OTDA uses multivariate logistic regression to predict an occupant's risk of sustaining an injury on the Master Target Injury List from the following model variables: longitudinal/lateral delta-v, number of quarter turns (in rollover only), belt status, multiple impacts, and airbag deployment.

A parametric OTDA was developed with five tunable parameters allowing for extensive optimization. The OTDA was optimized with a genetic algorithm that compared the OTDA transportation decision for each NASS-CDS occupant to a dichotomous representation of their Injury Severity Score (ISS). Occupants with ISS 16+ should be transported to a Level I/II TC. OTDA optimization minimized under triage (UT) and over triage (OT) rates with the goal of producing UT rates < 5% and OT rates < 50% as recommended by the American College of Surgeons (ACS). For the optimized OTDA, UT rates by crash mode were 5.9% (frontal), 4.6% (near side), 2.9% (far side), 7.0% (rear), and 16.0% (rollover). OT rates by crash mode for the optimized OTDA were 49.7% (frontal), 47.9% (near side), 49.7% (far side), 44.0% (rear), and 49.7% (rollover).

The OTDA was developed with an injury-based approach that examined three injury facets to identify injuries necessitating treatment at a Level I/II TC. Large hospital and survey datasets containing information on injuries, mortality risk, treatment urgency, and hospital transfers were used in conjunction with large crash datasets with crash, vehicle, occupant, and injury data. The OTDA has been rigorously optimized and has demonstrated improved UT rates compared to other AACN algorithms in the literature and OT rates meeting ACS recommendations. Since the OTDA uses only vehicle telemetry measurements specified in Part 563 regulation, this AACN algorithm could be readily incorporated into new vehicles to inform emergency personnel of recommended triage decisions for MVC occupants. The overall societal purpose of this AACN algorithm is to reduce response times, increase triage efficiency, and improve overall patient outcome.

INTRODUCTION

There are approximately 6.4 million motor vehicle crashes (MVCs) annually in the United States (US) [1]. These crashes killed 33,000 people and injured 3.9 million people in 2010 [2]. Many crashes leave a heavy burden of

morbidity that can affect victims throughout the rest of their lives. While the advent of passive safety standards (seat belts, airbags, etc.) has lowered the morbidity and mortality of motor vehicle crash victims, there are significant barriers to further improvements. Most experts believe that an important future avenue for progress is to improve the trauma triage process, that is, the process whereby patients are given the “right care” at the “right place” at the “right time.” Optimizing this process is difficult due to timing, decision making, resources, and access to care.

Advanced Automatic Crash Notification (AACN) has shown promise in improving the trauma triage process by predicting occupant injury severity using vehicle telemetry data to recommend a transportation decision. Event data recorders (EDRs) use electronic sensors in the car to collect crash data and AACN systems can transmit this data to the proper authorities. The 49 CFR Part 563 regulation for EDRs released by NHTSA specifies the data elements required for all vehicles equipped with an EDR [3]. Required data elements include longitudinal delta-v, seat belt status, frontal airbag deployment, and multiple events. The regulation also includes data elements required for vehicles under specified conditions. Data elements for these include lateral delta-v, vehicle roll angle, and side airbag deployment. Using the information collected from a vehicle, the risk of an occupant sustaining an injury can be calculated, and a decision process for determining the level of care for the occupant can be presented to emergency medical personnel. The National Study on the Costs and Outcomes of Trauma (NSCOT) identified a 25% reduction in mortality for severely injured patients who received care at a Level I trauma center rather than at a non-trauma center [4]. AACN technology can provide data on the vehicle location, delta-v, principal direction of force (PDOF), airbag deployment, and the occurrence of rollover or multiple event collisions which may be valuable in estimating the occupant’s injury risk following a MVC.

Current AACN algorithms include OnStar and URGENCY which incorporate model variables such as crash direction, delta-v, multiple impacts, belt use, vehicle type, age, and sex [5-11]. Both of these algorithms use Abbreviated Injury Scale (AIS) metrics to define severely injured patients. Although AIS-based metrics are most commonly used, other methods of injury scoring have been developed to better discriminate severely injured patients.

The objective of this study was to develop an AACN algorithm and evaluate its performance in making optimal occupant triage decisions using an injury-based approach. The developed AACN algorithm, known as the Occupant Transportation Decision Algorithm (OTDA), uses measurements obtainable from vehicle telemetry to predict risk of overall occupant injury and recommend a transportation decision for the occupant following a MVC.

METHODS

An injury-based approach quantifying three facets of individual injuries was developed to improve upon the severity scoring systems and better evaluate the risk of occupant injury. This approach focused on 240 injuries comprising the top 95% most frequently occurring AIS 2+ injuries in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) 2000-2011. The injury-based approach identifies injuries requiring Level I/II trauma center (TC) level treatment by quantifying three facets of injury: severity, time-sensitivity, and predictability. Severity is associated with injuries which have a high mortality and high threat-to-life. Severity was scored based on mortality risk ratios (MRRs) obtained from the National Trauma Data Bank (NTDB) [12]. Time Sensitivity is associated with the urgency with which a particular injury requires treatment. Time Sensitivity was scored using expert physician survey data which incorporated the recommended treatment location and a rank of urgency [13]. Predictability is associated with injuries with a propensity to be missed on evaluation at the scene. Predictability was scored using two components: an Occult Score and a Transfer Score. The Occult Score is a measure of the likelihood that an injury is missed using expert survey data from physicians and emergency medical services (EMS) professionals. The Transfer Score is a measure of the likelihood that an injury is present in patients that require transfer from a non-trauma center to a Level I/II TC using the National Inpatient Sample (NIS) database [14]. The scores of each of these facets (Severity, Time Sensitivity, and Predictability) were computed for each of the 240 injuries on the top 95% most frequently occurring AIS 2+ MVC injuries list. Each score was normalized on a zero to one scale in which scores closer to one were more severe, more time sensitive, and less predictable.

The inputs to the OTDA include a Master Target Injury List and NASS-CDS 2000-2011 cases. The Master Target Injury List is determined by multiplying the Severity, Time Sensitivity, and Predictability Scores by a weighting coefficient and then summing these values to produce a Target Injury Score. Injuries exceeding a defined Injury Score Cutoff are then included on the Master Target Injury List. The Master Target Injury List is not a static list and

is capable of being varied in order to optimize the algorithm. An example computation of the Target Injury Score is provided in Figure 1 for an AIS 3 vault fracture. The injury had Severity, Time Sensitivity, and Predictability Scores of 0.73, 0.93, and 0.48, respectively. These scores indicated a severe and time sensitive injury that has moderately high predictability and the Target Injury Score was 2.14. For this example, the weighting coefficients were set to one. However, optimization of the algorithm allows the weighting coefficients to vary as will be explained later.

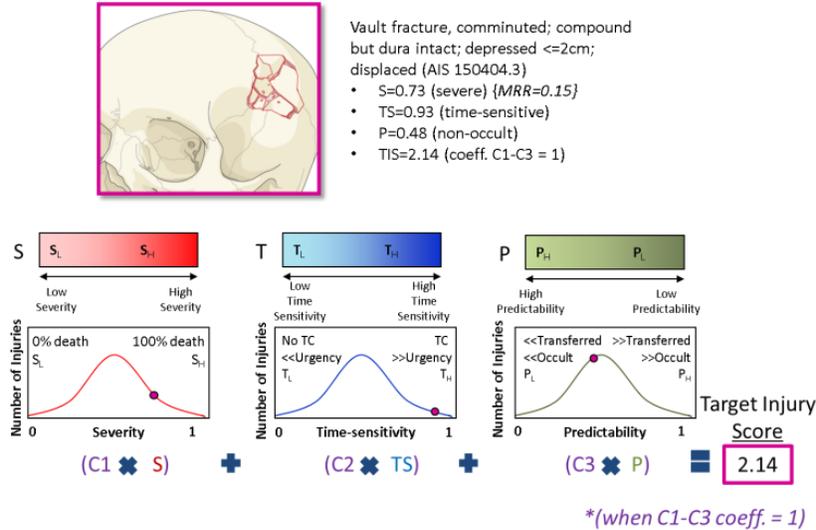


Figure 1. Example computation of a Target Injury Score for an AIS 3 vault fracture.

NASS-CDS 2000-2011 cases were used to train and evaluate the OTDA. Cases from NASS-CDS 2009-2011 with a model year greater than 10 years were excluded due to missing injury and occupant information (11,814 distinct occupant IDs excluded). After applying the exclusion criteria, the resulting NASS-CDS 2000–2011 dataset contained 54,703 cases, 94,283 vehicles, 115,159 occupants, and 303,230 injuries.

The OTDA uses multivariate logistic regression to predict the risk of an occupant sustaining an injury on the Master Target Injury List for specified crash conditions. Weighted NASS-CDS 2000-2011 data was used to select frontal, near side, far side, rear, and rollover crashes for driver and front right passengers 16 years and older. Five separate multivariate logistic regression models were created according to crash type: frontal, near side, far side, rear, and rollover crash. For determining the outcome measure, each occupant’s injuries were assessed to determine if any one of the injuries was on the Master Target Injury List. If at least one injury appeared on the Master Target Injury List that occupant was coded as sustaining a Target Injury; if none of the occupant’s injuries were on the Master Target Injury List, that occupant was coded as not sustaining a Target Injury.

Longitudinal delta-v was used for the frontal and rear models. Lateral delta-v was used in the near side and far side models. EDR correction factors for delta-v were implemented to adjust for differences in the delta-v estimated by WinSMASH in NASS and the delta-v obtained directly from the EDR [15-18]. For the rollover crash type, the number of quarter turns was binned into six categories: 1, 2, 3-4, 5-6, 7-8, 9-17. Any MVC with a quarter turn greater than 1 was categorized as rollover even if it met other crash mode criteria. Models for frontal, rear, and far side were adjusted for belt status, multiple impacts, and frontal airbag deployment. Models for near side and rollover were adjusted for belt status, multiple impacts, frontal and side airbag deployment. The majority of the variables included in the OTDA (longitudinal delta-v, belt status, multiple impacts, and frontal airbag deployment) were selected because they are EDR variables required for all vehicles in the EDR regulation, 49 CFR Part 563 [3]. Lateral delta-v and side airbag deployment were included because of their importance in defining crash severity for side impacts and they are EDR variables required for vehicles under specified conditions in 49 CFR Part 563. Occupants with any missing data for variables of interest were not included in the analysis. The Risk of any Target Injury is calculated with the cumulative distribution function for frontal, rear, and far side in Equation 1 and for near side and rollover in Equation 2. Logistic regression analyses were performed using SAS 9.4 (SAS Institute, Cary, NC) and R 3.0.2 (R Foundation for Statistical Computing, Vienna, Austria).

$$\frac{e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI)}}{1 + e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI)}} \quad (1).$$

where α = intercept, $\beta_1, \beta_2, \beta_3, \beta_4$ =parameter coefficients for DV= longitudinal delta-v/lateral delta-v; Belt= belt status (0=no, 1= yes); AB= frontal airbag deployment (0= no, 1=yes); MI= multiple impacts (0= no, 1= yes).

$$\frac{e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI + \beta_5 SAB)}}{1 + e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI + \beta_5 SAB)}} \quad (2).$$

where α = intercept, $\beta_1, \beta_2, \beta_3, \beta_4$ =parameter coefficients for DV= lateral delta-v/number of quarter turns; Belt= belt status (0=no, 1= yes); AB= frontal airbag deployment (0= no, 1=yes); MI= multiple impacts (0= no, 1= yes); SAB= side airbag deployment (0=no, 1=yes).

The OTDA features five tunable parameters (termed “Variable Parameters”) allowing for extensive optimization. The five Variable Parameters include the Severity Multiplier, Time Sensitivity Multiplier, Predictability Multiplier, Injury Score Cutoff, and a Risk Cutoff. The Severity Multiplier, Time Sensitivity Multiplier, and Predictability Multiplier are the weighted coefficients used to produce the Target Injury Score. The Injury Score Cutoff is the threshold at which an injury is deemed to be included on the Master Target Injury List. The Risk Cutoff is the threshold above which a case is deemed recommended to be sent to a Level I/II TC.

The OTDA was optimized with a Covariance Matrix Adaptation- Evolution Strategy (CMA-ES) genetic algorithm that compared the OTDA transportation decision for each NASS-CDS occupant to a dichotomous representation of their Injury Severity Score (ISS). Occupants with ISS 16+ should be transported to a Level I/II TC. OTDA optimization minimized under triage (UT) and over triage (OT) rates with the goal of producing UT rates < 5% and OT rates < 50% as recommended by the American College of Surgeons (ACS) [19]. OT was assessed using the False Positive Rate (FPR) metric, also known as 1-Specificity [20-22]. This represents the proportion of mildly injured patients that went to a Level I/II TC. UT was assessed using the False Negative Rate (FNR) metric, also known as 1-Sensitivity [20-23]. This represents the proportion of seriously injured patients that did not go to a Level I/II TC. A graphical representation of the OTDA is provided in Figure 2.

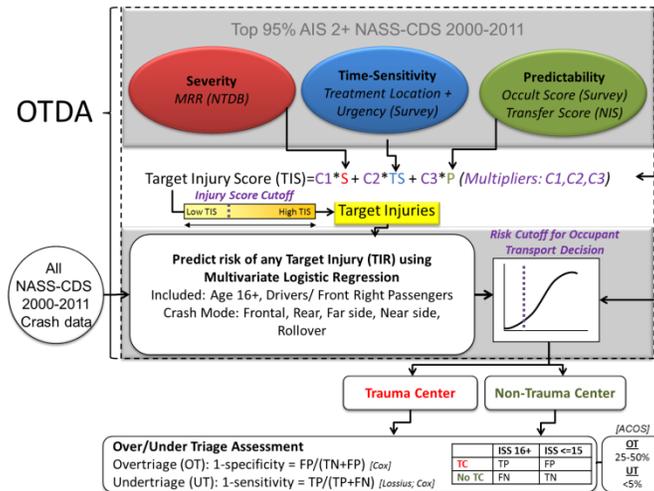


Figure 2. Overview of OTDA.

RESULTS

A total of 38,970 NASS-CDS 2000-2011 cases met the inclusion criteria and the number of cases by crash mode is summarized in Table 1.

Table 1.
Cases meeting inclusion criteria by crash mode.

Crash Mode	# of Cases
Frontal	21,273
Rear	2,667
Far side	3,608
Near side	3,890
Rollover	7,082
Total	38,970

The resulting OT and UT metrics for the optimal Variable Parameters are listed in Table 2.

For the optimized OTDA, UT rates by crash mode were 5.9% (frontal), 7.0% (rear), 2.9% (far side), 4.6% (near side), and 16.0% (rollover). OT rates by crash mode for the optimized OTDA were 49.7% (frontal), 44.0% (rear), 49.7% (far side), 47.9% (near side), and 49.7% (rollover). The UT rates for far side and near side met the 5% ACS recommendation. The OT rates for frontal, rear, far side, near side, and rollover all met the 50% ACS recommendation.

Table 2.
OT/UT metrics by crash mode for the optimal Variable Parameters.

Crash Mode	OT Metric (FPR)	UT Metric (FNR)	TP	FP	TN	FN
Frontal	49.7%	5.9%	903	10451	10312	57
Rear	44.0%	7.0%	40	1470	1154	3
Far side	48.7%	2.9%	232	1727	1642	7
Near side	47.9%	4.6%	559	1723	1581	27
Rollover	49.7%	16.0%	871	3040	3005	166

DISCUSSION

The OTDA was developed with an injury-based approach that examined three injury facets to identify injuries necessitating treatment at a Level I/II TC. Large hospital and survey datasets containing information on injuries, mortality risk, treatment urgency, and hospital transfers were used in conjunction with large crash datasets with crash, vehicle, occupant, and injury data. The OTDA has been rigorously optimized and has demonstrated improved UT rates compared to other AACN algorithms in the literature and OT rates meeting ACS recommendations. For studies using URGENCY where separate models were created by crash mode, the UT rates ranged from 29-49% for frontal crashes, 6-33% for near side crashes, and 19-46% for far side crashes [8-11, 24]. For the OT rates, the values ranged from 3-18% for frontal crashes, 5-46 % for near side crashes, and 10-15% for far side crashes.

Traditionally, priority has been given to the reduction of UT to prevent mortality & morbidity with the understanding that some elevation in OT is necessary to prevent seriously injured patients from being under triaged. The OTDA significantly reduced UT for all crash modes without elevating OT beyond the ACS guidelines. These results are very encouraging as the OTDA uses only crash characteristics that are obtainable from vehicle sensors, whereas the majority of AACN algorithms in the literature use variables such as occupant age or gender that are not obtainable directly from the vehicle. In short, the OTDA appears to be doing “more with less” than several algorithms to which it has been compared and shows great promise as an improved approach for triaging patients.

Additional reduction in UT and OT would be expected if additional variables such as occupant age and gender were included in the OTDA. There is some room for improvement in UT for rollover crashes. Rollover crashes are complex events and determining the severity of the event is difficult due to many factors. These factors include vehicle geometry, vehicle deformation, and subsequent impacts which can alter the number of quarter turns a vehicle experiences. Several studies have taken different approaches to determine rollover severity by using the number of quarter turns [25], the number of ground to roof impacts [25], the extent of roof crush [26], pre-roll speed [6], and primary area of damage [26]. The NASS rollover variable which designates the number of quarter turns has

been previously used in URGENCY and other studies involving rollover research [8, 11, 27-31]. Additional data elements could be incorporated in the future to better quantify the severity as well as a better differentiation of the types of rollovers.

Overall, side airbag deployment resulted in little difference in the OT/UT rates for near side and rollover crashes. However, for the cases that involved vehicles that deployed a side airbag, the UT rates were improved, but this is less evident when looking at the entire NASS-CDS sample since only 5-10% of the vehicles were equipped with side airbags. Therefore, with the inclusion of the side airbag variable there would be a benefit for the occupant in vehicles where a side airbag is equipped.

Since the OTDA uses only vehicle telemetry measurements specified in Part 563 regulation, this AACN algorithm could be readily incorporated into new vehicles to inform emergency personnel of recommended triage decisions for MVC occupants. The overall societal purpose of this AACN algorithm is to reduce response times, increase triage efficiency, and improve overall patient outcome.

CONCLUSION

An AACN algorithm, known as the OTDA, was developed that utilizes MVC characteristics obtainable from vehicle telemetry data and estimates the risk of serious injury for occupants. This risk for injury is used to recommend a transportation decision for the occupant (Level I/II TC versus non-trauma center). A parametric algorithm was developed with tunable parameters to allow for extensive optimization. Adjusting the Severity, Time Sensitivity, and Predictability Multipliers changes the taxonomy of injuries on the Master Target Injury List. The Injury Score Cutoff changes the number of Target Injuries that are included on the Master Target Injury List. The Risk Cutoff adjusts the level of risk that defines whether an occupant should be treated at a Level I/II TC versus a non-trauma center. The rigorous optimization of the OTDA produced improved UT rates compared to other AACN algorithms in the literature and OT/UT rates that met the ACS recommendations.

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