SafeTREC Safe Transportation Research & Education Center

WP-2012-1

The relative vulnerability index: a framework for evaluating multimodal traffic safety

Offer Grembek
SafeTREC, UC Berkeley
www.safetrec.berkeley.edu
August 2012

The relative vulnerability matrix: a framework for evaluating multimodal traffic safety

Offer Grembek*

Safe Transportation Research & Education Center, University of California, Berkeley

Abstract

The multimodal transportation network includes a mix of inherently different modes. In addition to differences in price, range, and comfort of travel, these modes differ in mass and velocity, which correspond to different orders of magnitude in the kinetic energy carried. This discrepancy in kinetic energy affects both the level of protection of each mode, and the level of damage it can inflict on users of other modes. Unfortunately, accounting for both sides of a crash is often overlooked. While the quantities and variables of collected data continue to increase, the analyses conducted and the tools developed remain focused on the victims of crashes. The existing approach limits the ability to explore the underlying mechanism of traffic crashes since there are two sides to every crash. This manuscript proposes a framework for studying traffic safety which takes into account the interaction between all modes in a network. At the core of the framework is a square matrix, I. The rows and columns represent different modes such that element I_{ij} is the number of injuries that were suffered by mode i which were inflicted by mode j. The distinction between suffered and inflicted injuries is not related to the fault of the involved parties. The distinction lies in which of the two parties experienced the injury. For example, if two vehicles are involved in a crash that resulted in a single injury, the vehicle that experienced the injury is identified as the one that suffered the injury while the other vehicle is the one that inflicted the injury. If an injury is experienced in both vehicles then both vehicles suffered one injury and inflicted one injury. A relative vulnerability index can be calculated for specific mode-pairs, for individual modes, and for an entire geographical region. An empirical application using data from California reveals, amongst other things, that the relative vulnerability of pedestrian and bicyclist are orders of magnitude higher than motorized modes. Applying this methodology to different locations around the globe would provide insights the relative vulnerability of different modes under different mode-splits, different road designs, and different road user cultures.

Keywords: Relative vulnerability, traffic safety, exposure, mode share

1. Introduction

The multimodal transportation network includes a mix of inherently different modes. In addition to differences in cost, range, and comfort of travel, these modes differ in mass and velocity, which correspond to different orders of magnitude in the kinetic energy carried. This discrepancy in kinetic energy affects both the level of protection to users of each mode, and the level of damage it can inflict on users of other modes. Unfortunately, accounting for both sides of a crash is often overlooked. Instead, the emphasis lies in one-sided studies analyzing the suffered injury rates. This manuscript proposes a framework for studying traffic safety which takes into account the interaction between all modes in a transport network.

While the quantities and number of road safety variables continue to increase, the analyses conducted and the tools developed remain focused on the victims of crashes. The existing approach limits the ability to explore the underlying mechanism of traffic crashes which involves both sides of a crash. By analogy, knowing the number of points scored by the home team in a basketball game is insufficient to reveal the outcome of that game. Similarly, data about the

*Corresponding author
Email address: grembek@berkeley.edu (Offer Grembek)

number of punches suffered by a boxer during a boxing fight does not reveal the outcome, until one knows the number of punches inflicted on the opponent. These examples highlight the fact that focusing on the victims of crashes is not enough to understand the dynamics of safety across a multimodal transportation network.

Moreover, the analysis conducted and the tools developed are focused on uni-modal analyses. Researchers tend to develop expertise in safety of a specific mode and study the implications of various factors on the safety of that mode. While this facilitates progress in our understanding of safety for specific modes it limits our understanding of the implications of interacting with other modes.

Analyzing the multimodal safety is critical in both developed and developing areas of the world. In developing countries, vehicles entering environments where there are, and will continue to be, lots of walking and bicycling. In already developed countries, laws, policies, and economic factors are at play that will likely lead to increased walking, biking, and transit mode-share in coming years. In both cases, recognition of the enormous environmental impact of a vehicle-based transportation system will lead to programs and policies to maintain or increase alternative modes of transportation.

By 2020, road deaths are forecast to double, with the burden falling most heavily on low- and middle-income countries and, within those countries, on the most vulnerable and poorest road users. Half of the 1.2 million people killed and half of the 50 million injured in road crashes in 2009 were pedestrians, motorcyclists, cyclists, and passengers on public transport; and more than 90 percent were from low- and middle-income countries [1]. While low- and middle income countries experience rapid increases in the multimodal traffic due to motorization, high income countries, especially in urban areas, have been faced with multimodal environments for several decades. Without doubt, we will be dealing with multimodal environments for a long time to come, and addressing traffic safety in multimodal environments is now of critical importance.

The remainder of the paper is organized as follows. The next section will present the proposed framework along with the necessary definitions. Following this the data requirements for compiling the proposed matrix is presented. A case study of applying this analysis for California injury data is presented next, followed by comparison across different counties. Finally, some concluding remarks about the limitation and advantages of this approach are provided.

2. The Multimodal Injury Matrix

At the core of the framework is a square matrix, I, of dimension n. The rows and columns represent n different modes such that element I_{ij} is the number of injuries that were suffered by mode i which were inflicted by mode j. The distinction between suffered and inflicted injuries is not related to the fault of the involved parties. The distinction lies in which of the two parties experienced the injury. For example, if two vehicles are involved in a crash that resulted in an injury in only one vehicle, the vehicle that experienced the injury is identified as the one that *suffered* the injury while the other vehicle is the one that *inflicted* the injury. If an injury is experienced in both vehicles then both vehicles suffered one injury and inflicted one injury. Furthermore, since over 20% of traffic crashes involve only one party (ref) an inanimate mode, labeled *Object*, is added to the matrix. By definition this inanimate mode can only inflict damage. To prevent double-counting of injuries, the data in I is restricted to crashes involving two or fewer parties, which account for approximately 85% of all crashes (ref).

For illustration purposes an example using pedestrians, passenger cars, trucks, and inanimate objects is provided below:

$$I = \begin{array}{c} \\ Foot \\ Car \\ Truck \\ Object \end{array} \begin{array}{c} \begin{array}{cccc} Foot & Car & Truck & Object \end{array} \\ \begin{pmatrix} I_{11} & I_{12} & I_{13} & I_{14} \\ I_{21} & I_{22} & I_{23} & I_{24} \\ I_{31} & I_{32} & I_{33} & I_{34} \\ I_{41} & I_{42} & I_{43} & I_{44} \end{pmatrix} \end{array}$$

For this example, the elements in column $j = 2$ represent the number of injuries inflicted by cars across the different modes. Element I_{12} is the number of pedestrian injuries inflicted by cars, element I_{22} is the number of car occupant injuries inflicted by other cars, element I_{32} is the number of truck occupant injuries inflicted by cars, and $I_{42} \equiv 0$ since inanimate objects cannot suffer any injuries.

Similarly, the elements in row $i = 2$ represent the number of injuries suffered by cars across the different modes. Where, element I_{21} is the number of car occupant injuries inflicted by pedestrians, element I_{22} is the number of car occupant injuries inflicted by other cars, element I_{23} is the number of car occupant injuries inflicted by trucks, and I_{42} is the number of injuries suffered in crashes that involve a single car. Note, that while it is unlikely for a car to injur truck occupants, it is possible for a truck to suffer an injury as a result of a crash with a car. For example, if a truck loses control as a result of a crash with a car, and suffers an injury, it is considered a truck injury inflicted by a car. The same logic is applied for injuries inflicted by pedestrians or bicyclists on motorized modes. As mentioned earlier inanimate objects can only inflict injury and therefore, by definition, the elements of the last row are always 0.

The Injury Matrix, I, provides a comprehensive snapshot of safety across a specific entity. This includes the number of injuries suffered by mode i, calculated as the sum of each row, as shown in Equation 1. For example, for $i = 1$ it is the number of pedestrian injuries suffered.

$$I_{i\bullet} = \sum_{j=0}^{n} I_{ij} \tag{1}$$

Similarly, the number of injuries inflicted by mode j is calculated as the sum over an individual column, as shown in Equation 2. For example, for $j = 1$ it is the number injuries inflicted by pedestrians.

$$I_{\bullet j} = \sum_{i=0}^{n} I_{ij} \tag{2}$$

Finally, the total number of injuries, involving two or fewer parties, across all modes, is calculated as the sum across all elements in the matrix, as shown in Equation 3.

$$I_{\bullet\bullet} = \sum_{i=1}^{n} \sum_{j=1}^{n} I_{ij} \tag{3}$$

The Injury Matrix reveals valuable information about the safety of each mode, and also about the dynamics between modes in terms of safety. In other words, what modes are inflicting injuries on what modes. As shown, these insights can be extracted with very little effort.

3. The Relative Vulnerability

The Relative Vulnerability (RV) is defined as the ratio between the number of injuries inflicted by a mode to the number of injuries suffered by a mode. Using Injury Matrix, I, it is possible to calculate this ratio for three different levels of analysis: (i) specific mode pairs; (ii) individual modes; and (iii) across all modes in a region.

3.1. Specific mode-pairs

The RV for a specific mode-pair is the ratio between the number of injuries suffered by mode i to the number of injuries suffered by mode j in crashes between modes i and j, as shown in Equation 4.

$$V_{ij} = \frac{I_{ij}}{I_{ji}}, \quad \text{and} \quad V_{ji} = \frac{1}{V_{ij}} \tag{4}$$

When applied to all mode-pairs, a relative vulnerability matrix, V, can be constructed as shown below:

$$V = \begin{array}{c} \\ Foot \\ Car \\ Truck \\ Object \end{array} \begin{array}{c} \begin{array}{cccc} Foot & Car & Truck & Object \end{array} \\ \begin{pmatrix} V_{11} & V_{12} & V_{13} & V_{14} \\ V_{21} & V_{22} & V_{23} & V_{24} \\ V_{31} & V_{32} & V_{33} & V_{34} \\ V_{41} & V_{42} & V_{43} & V_{44} \end{pmatrix} \end{array}$$

For each mode-pair in V the users of mode i suffer V_{ij} times more injuries than they inflict, in crashes with mode j. Therefore, for the example above, $V_{12} = I_{12}/I_{21}$ represents how many times more do the number of times pedestrians suffer in crashes with cars compared with the number of injuries pedestrians inflict on car occupants. In other words, V_{12} represents the RV of pedestrian in crashes with cars. Since pedestrians are the more vulnerable party in crashes with cars this number is expected to be much greater than 1. Accordingly, $V_{22} \equiv 1$, and $V_{32} = I_{32}/I_{23}$ is expected to be less than 1 since in crashes between these two modes, truck occupants are likely to suffer fewer injuries than they inflict on car occupants.

3.2. Individual modes

The RV for individual modes is the ratio between the number of injuries suffered by users of a particular mode and the number of injuries that mode inflicts across all modes. This is calculated as the number of injuries suffered by users of mode i, divided by the number of injuries inflicted in crashes with mode i, as shown in Equation 5:

$$V_i = \frac{I_{\bullet j}}{I_{i\bullet}} \tag{5}$$

At the individual mode level these values reflect the RV considering outcomes of conflicts across all modes. Therefore, for the above example we expect the RV of pedestrians to be much greater than that of car occupants, which, in turn, is expected to be greater than that for truck occupants (i.e., $V_1 \gg V_2 \gg V_3 \gg V_4 = 0$). The RV of individual modes depends on the traffic mix in the study area.

3.3. Across all modes

Using this framework it is also possible to estimate the RV in a geographical region. This takes into account all the modes in that region and weighs the RV for the individual modes by the mode share of each mode. This is done by multiplying a vector of the RV for individual modes, labeled $v = [V_1, V_2, \ldots, V_n]$, by a vector of exposure, e, for these modes.

4. Data requirements

This section describes the data requirements for compiling the Multimodal Injury Matrix. Since different transportation agencies use different databases this section describes the minimum data elements needed for this purpose, as summarized Table 1. In practice, these data elements may be gathered from different sources or tables.

The table also includes five examples of possible observations. As shown, the unit observation is a single crash that involves two parties or fewer. For each crash there needs to be information about the type of mode (e.g., pedestrian, car, SUV, etc.), and about the number of injuries experienced in each of these modes. The database also needs to include time and locations variables. Any additional variables can be used to stratify the analysis by different categories (rural crashes, urban crashes, crash severity.)

Table 1: Minimum Data Needed to compile the Multimodal Crash Matrix

Crash ID	Mode 1 Type	Mode 1 Injuries	Mode 2 Type	Mode 2 Injuries	Time/Date Variables	Location Variables	Other Variables
1	Foot	1	Car	0	-	-	-
2	Car	1	Car	1	-	-	-
3	Car	2	Object	0	-	-	-
4	Truck	0	Car	1	-	-	-
5	Foot	1	Truck	0	-	-	-

Table 1 can also serve as a numerical example of how the raw data is converted to the Multimodal Injury Matrix. The 7 injuries that were experienced in the five crashes in Table 1 are now displayed in the matrix below:

$$I = \begin{array}{c} \\ Foot \\ Car \\ Truck \\ Object \end{array} \begin{array}{c} \begin{array}{cccc} Foot & Car & Truck & Object \end{array} \\ \begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & 2 & 1 & 2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

5. Findings for California

The above definitions and data preparation guidelines were applied for a five year period for crashes in California. Injury crashes involving up to two parties between 2005 and 2009 were compiled using the California Statewide Integrated Traffic Records System (SWITRS) database. The data includes injuries of all severity levels.

5.1. Multimodal Injury Matrix for California

As shown in matrix I below, eight different modes were evaluated. As expected, the highest number of injuries is from crashes is between two cars (221, 444 injuries). As mentioned before, the sum across each row is the number of injuries experienced by a specific mode. For California the number of car occupant injuries is 432, 822, which reveals that only about half of the injuries suffered by car occupants are experienced in crashes between two cars. Note, that the second highest number of car occupant injuries is experienced in crashes with an inanimate object (110, 105), and the third is in crashes with SUV's (76, 543).

$$I = \begin{array}{c} \\ Foot \\ Bicycle \\ PTW \\ Car \\ Transit \\ SUV \\ Truck \\ Object \end{array} \begin{array}{c} \begin{array}{cccccccc} Foot & Bicycle & PTW & Car & Transit & SUV & Truck & Object \end{array} \\ \begin{pmatrix} 31 & 488 & 327 & 32,455 & 631 & 5,736 & 531 & 3 \\ 195 & 1,551 & 213 & 28,657 & 320 & 4,833 & 397 & 1,655 \\ 159 & 106 & 4,847 & 21,036 & 118 & 4,199 & 647 & 8,864 \\ 607 & 331 & 2,814 & 221,444 & 2,655 & 76,543 & 18,323 & 110,105 \\ 28 & 15 & 10 & 2,829 & 578 & 596 & 347 & 474 \\ 66 & 46 & 332 & 43,543 & 330 & 23,403 & 3,262 & 19,213 \\ 2 & 5 & 18 & 2,305 & 58 & 578 & 1,638 & 1,663 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

5.2. Specific mode-pairs

Based on matrix I it is now possible to estimate the RV for specific mode pairs, as shown in matrix V below:

$$V = \begin{array}{c} \\ Foot \\ Bicycle \\ PTW \\ Car \\ Transit \\ SUV \\ Truck \\ Object \end{array} \begin{array}{c} \begin{array}{cccccccc} Foot & Bicycle & PTW & Car & Transit & SUV & Truck & Object \end{array} \\ \begin{pmatrix} 1.00 & 2.50 & 2.06 & 53.47 & 22.54 & 86.91 & 265.50 & - \\ 0.40 & 1.00 & 2.01 & 86.58 & 21.33 & 105.07 & 79.40 & - \\ 0.49 & 0.50 & 1.00 & 7.48 & 11.80 & 12.65 & 35.94 & - \\ 0.02 & 0.01 & 0.13 & 1.00 & 0.94 & 1.76 & 7.95 & - \\ 0.04 & 0.05 & 0.08 & 1.07 & 1.00 & 1.81 & 5.98 & - \\ 0.01 & 0.01 & 0.08 & 0.57 & 0.55 & 1.00 & 5.64 & - \\ 0.00 & 0.01 & 0.03 & 0.13 & 0.17 & 0.18 & 1.00 & - \\ - & - & - & - & - & - & - & 1.00 \end{pmatrix} \end{array}$$

As described earlier, these values are calcuated directly from matrix I. For example, according to the data the RV between pedestrian and bicyclsits is $V_{12} = 488/195 = 2.5$, which means that pedestrian suffer 2.5 times more injureis tahn they inflcit on bicyckes in crashes between pedestrian and bicyclys. Note, that $V_{21} = 0.4$ as the inverse value. The data also reveals that in California, pedestrians are more vulnerable in crashes with SUVs (86.91) than they are in crashes with passenger cars (53.47). Since passenger cars and SUVs exhibit different vehicle design, this may indicate that there may be potential for changes in vehicle design to reduce pedestrian vulnerability. Also, the data reveals that in California, pedestrians are more vulnerable in crashes with cars (53.47) than they are in crashes with transit (22.54).

This may be because crashes between pedestrians and transit may more likely to occur in dense urban areas, where the speed of transit is relatively low, while crashes between pedestrians and cars may be more likely to occur in higher speed rural environments.

5.3. Individual Modes

We can also calculate the RV for individual modes, as shown by the vector below. For California it reveals that pedestrians and bicyclists experience a relative vulnerability with a different order of magnitude (36.95 and 14.88 respectively) and that they can indeed be considered vulnerable road users. In the California mode-mix, truck occupants have the lowest relative vulnerability, while trucks inflict four times the number of injuries their occupants suffer. Occupants of passenger cars have a relative vulnerability of 1.23 which indicates that they suffer from more injuries than they inflict. This is partly due to crashes with inanimate objects, which are by definition absolutely invulnerable.

$$\begin{array}{r} \\ California \end{array} \begin{array}{c} \begin{array}{cccccccc} Foot & Bicycle & PTW & Car & Transit & SUV & Truck & Object \end{array} \\ \begin{pmatrix} 36.95 & 14.88 & 4.67 & 1.23 & 1.04 & 0.78 & 0.25 & 0.00 \end{pmatrix} \end{array}$$

5.4. Comparing across different counties

The matrix below summarizes the relative vulnerability for users of individual modes in California and in three California counties. The same order of magnitude is maintained in the three counties presented the matrix below. However, the relative vulnerability for the individual modes differs across the different counties. For example, the relative vulnerability for pedestrians in LA Country is 46.31 while in San Francisco it is much lower level of 27.86. The sources of these differences have not been thoroughly explored yet. However, given the difference in urban structure and land use patterns across these counties it is possible that some of these discrepancies are associated with such variables.

$$\begin{array}{r} \\ California \\ LosAngeles \\ Alameda \\ SanFrancisco \end{array} \begin{array}{c} \begin{array}{cccccccc} Foot & Bicycle & PTW & Car & Transit & SUV & Truck & Object \end{array} \\ \begin{pmatrix} 36.95 & 14.88 & 4.67 & 1.23 & 1.04 & 0.78 & 0.25 & 0.00 \\ 46.31 & 16.46 & 5.16 & 1.07 & 0.99 & 0.69 & 0.23 & 0.00 \\ 40.88 & 18.43 & 6.31 & 1.12 & 1.10 & 0.65 & 0.21 & 0.00 \\ 27.86 & 8.13 & 5.45 & 0.69 & 0.65 & 0.45 & 0.17 & 0.00 \end{pmatrix} \end{array}$$

6. Discussion

Applying this methodology to California reveals different levels of vulnerability across the different ent modes of the transportation network. Also, it demonstrates that the transportation modes like pedestrians and bicyclists are indeed much more vulnerable than motorized modes, and labeling them as vulnerable road users, as is commonly done, is appropriate. The framework presented here is intended to be used as a tool to facilitate exploratory analysis in the field of traffic safety. Insights can be withdrawn from comparing design features across regions that have different levels of RV. Similarly, this can be used to track changes over time that may occur due to changes in land-use, mode-share, traffic operations and regulations. Moreover, this can guide discussion to think of potential unintended implications of these types of changes across all modes of the transportation network. One of the challenges of using this approach is the fact that different agencies may have very different definitions of data which may complicate these types of comparisons.

7. Conclusions

The relative vulnerability matrix approach has several features that make it easy to apply:

- provides a snapshot of the multimodal safety in a geographic region
- scalable

- easy to interoperate
- does not require a lot of data, or new data

By applying the proposed approach to different locations around the globe it would be possible to explore the relative vulnerability of different modes under different mode-splits, different road designs, and different road user cultures. This approach captures the challenging dynamics of studying road safety in multimodal environments, which will be one of the major challenges for the traffic safety field in years to come.

8. References

[1] World Health Organization, 2009. Global status report on road safety: time for action. Tech. rep., Geneva.
URL http://www.who.int/violence_injury_prevention/road_safety_status/2009/