# Relative Vulnerability Matrix for Evaluating Multimodal Traffic Safety

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**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 that 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 *Iij* 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.

## BACKGROUND

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 of a specific mode, which is limited for multimodal environments (Awad and Janson 1998, Fitzpatrick et. al 2006, Jama et. al. 2011, Knipling et al. 2003, Thompson et. al 1989). By analogy, knowing the number of points scored by the home team in a basketball game is insufficient to reveal the outcome of a game. Similarly, data about the 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. The conjecture here is that traffic safety should be studied while taking into account the multimodal nature of the transportation network.

At the core of the proposed 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 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. Furthermore, since over 20% of traffic crashes involve only one party 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.

## CASE STUDY FOR CALIFORNIA

Using these definitions, injury crashes involving up to two parties between 2005 and 2009 were compiled using the California Statewide Integrated Traffic Records System (SWITRS) database, and processed across eight different modes, as shown in Figure 1 below.

| Injury crashes in California (2005-2009) | | Mode *j* Involved/Inflicted an injury | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Foot** | **Bicycle** | **PTW** | **Car** | **Transit** | **SUV** | **Truck** | **Object** | **Total** |
| **Mode *i* Suffered an injury** | **Foot** | 31 | 488 | 327 | 32,455 | 631 | 5,736 | 531 | 3 | **40,202** |
| | **Bicycle** | 195 | 1,551 | 213 | 28,657 | 320 | 4,833 | 397 | 1,655 | **37,821** |
| | **PTW** | 159 | 106 | 4,847 | 21,036 | 118 | 4,199 | 647 | 8,864 | **39,976** |
| | **Car** | 607 | 331 | 2,814 | 221,444 | 2,655 | 76,543 | 18,323 | 110,105 | **432,822** |
| | **Transit** | 28 | 15 | 10 | 2,829 | 578 | 596 | 347 | 474 | **4,877** |
| | **SUV** | 66 | 46 | 332 | 43,543 | 330 | 23,403 | 3,262 | 19,213 | **90,195** |
| | **Truck** | 2 | 5 | 18 | 2,305 | 58 | 578 | 1,638 | 1,663 | **6,267** |
| | **Object** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| | **Total** | **1,088** | **2,542** | **8,561** | **352,269** | **4,690** | **115,888** | **25,145** | **141,977** | **652,160** |

FIGURE 1: Relative vulnerability matrix for California (Source: Grembek, 2012)

As expected, the highest number of injuries is a result of crashes between two cars (221,444 injuries). The second highest number of car occupant injuries is experienced in crashes with an inanimate object (110,105), and the third is car occupant injuries experienced in crashes with SUV's (76,543). As mentioned earlier, inanimate objects can only inflict injury and therefore, by definition, the elements of the last row are always 0. Note, that while it is unlikely for a car to injure 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.

The matrix provides a transparent and easy to interpret snapshot of safety across a region. It is intuitive to see that the sum across each row is the number of injuries experienced by each mode, and that the sum across each column is the number of injuries inflicted by each mode. The sum across the full matrix is the total number of injuries across a region (652,160 for California).

<u>Relative Vulnerability</u>

The Relative Vulnerability (RV) is defined as the ratio between the numbers 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.

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 1.

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

When applied to all mode-pairs, a relative vulnerability matrix, *V,* can be constructed as shown in Figure 2 below.

| RV for specific mode-pairs | | Mode *j* Involved/Inflicted an injury | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Foot | Bicycle | PTW | Car | Transit | SUV | Truck | Object |
| Mode *i* Suffered an injury | Foot | 1.00 | 2.50 | 2.06 | 53.47 | 22.54 | 86.91 | 265.50 | - |
| | Bicycle | 0.40 | 1.00 | 2.01 | 86.58 | 21.33 | 105.07 | 79.40 | - |
| | PTW | 0.49 | 0.50 | 1.00 | 7.48 | 11.80 | 12.65 | 35.94 | - |
| | Car | 0.02 | 0.01 | 0.13 | 1.00 | 0.94 | 1.76 | 7.95 | - |
| | Transit | 0.04 | 0.05 | 0.08 | 1.07 | 1.00 | 1.81 | 5.98 | - |
| | SUV | 0.01 | 0.01 | 0.08 | 0.57 | 0.55 | 1.00 | 5.64 | - |
| | Truck | 0.00 | 0.01 | 0.03 | 0.13 | 0.17 | 0.18 | 1.00 | - |
| | Object | - | - | - | - | - | - | - | 1.00 |

FIGURE 2: Relative vulnerability matrix for California

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.

As described earlier, these values are calculated directly from matrix $I$. For example, according to the data the RV between pedestrian and bicyclists is $V_{12} = 488/195 = 2.5$, which means that pedestrian suffer 2.5 times more injuries than they inflict on bicycles in crashes between pedestrian and bicycles. 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.

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 2 below:

$$V_i = \frac{I_{\bullet j}}{I_{i \bullet}} \qquad (2)$$

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. We can calculate the RV for individual modes, as shown in Figure 3 below.

| RV for different locations | Foot | Bicycle | PTW | Car | Transit | SUV | Truck | Object |
|---|---|---|---|---|---|---|---|---|
| RV for California | 36.95 | 14.88 | 4.67 | 1.23 | 1.04 | 0.78 | 0.25 | 0.00 |

FIGURE 3: Relative vulnerability for California

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.

Figure 4 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.

| RV for different locations | Foot | Bicycle | PTW | Car | Transit | SUV | Truck | Object |
|---|---|---|---|---|---|---|---|---|
| RV for California | 36.95 | 14.88 | 4.67 | 1.23 | 1.04 | 0.78 | 0.25 | 0.00 |
| RV for Los Angeles County | 46.31 | 16.46 | 5.16 | 1.07 | 0.99 | 0.69 | 0.23 | 0.00 |
| RV for Alameda County | 40.88 | 18.43 | 6.31 | 1.12 | 1.10 | 0.65 | 0.21 | 0.00 |
| RV for San Francisco County | 27.86 | 8.13 | 5.45 | 0.69 | 0.65 | 0.45 | 0.17 | 0.00 |

FIGURE 4: Relative vulnerability for California and three California Counties

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 $v = [V_1 , V_2 , . . . , V_n ]$, by a vector of exposure, $e$, for these modes.

## DISCUSSION AND CONCLUSIONS

Applying this methodology to California reveals different levels of vulnerability across the different 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 that may complicate these types of comparisons.

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
- is not data intensive

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.

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