Tay R (2000). The Prisoners' Dilemma: A Game Theoretic Approach to Vehicle Safety. Paper presented at the Road Safety Research, Policing & Education Conference, Brisbane, Australia.

The Prisoners' Dilemma: A Game Theoretic Approach to Vehicle Safety

Dr Richard Tay *
Queensland University of Technology

Abstract

This paper assessed the policy implications of the changing demand for passenger vehicles in Australia and debunked the myth that bigger vehicles are safer. In particular, we examined the increasing demand for small cars and four-wheel drive using the classic prisoners' dilemma framework in game theory. We found that the current emphasis on occupant protection may result in a pareto inferior outcome whereas a shift in the emphasis towards non-aggressiveness of a vehicle would result in a pareto superior outcome. Among the pure strategy equilibria, the one with only small cars provides the lowest overall level of road trauma. Furthermore, we found no mixed strategy equilibrium that would produce a lower level of trauma than the pure strategy equilibria, implying that mixing vehicle type would definitely increase road trauma. In a mixed fleet, however, medium cars produced the least trauma and thus were the safest type of passenger vehicle.

Introduction

Vehicle safety has been a major concern in the road safety arena over the last few decades and the conventional approach to vehicle safety regulations in most countries tends to focus on the crashworthiness of the vehicle and its occupant protection capability. Although some countries, including Australia, have began to examine the non-aggressiveness of vehicles (minimum damage to non-occupants including pedestrians, cyclist and occupants of other vehicles), most of the analyses are still concentrated on the crashworthiness of the vehicle and its occupant protection. Furthermore, most reports in the media are also primarily concerned about occupant protection and placing non-aggressiveness in a subservient position. For example, a sample of recent headings of articles in one major Australian newspaper includes "When big is safer", "Play it safe - drive a 4WD", "Small car crash tests take a battering from watchdog" and "Parents urged to steer teens clear of tiny cars".[1]

This misplaced emphasis played a major role in the general misconception that bigger vehicles were safer and might have contributed to the inefficiencies in resource allocation in the vehicle manufacturing industry and the road safety sector. Even though some of the vehicle design changes are expected to improve the protection of both occupants and non-occupants, many of the design parameters involve trade-offs between the two. In a survey of college students in New Zealand, Tay [1] found that students were more concerned about the likelihood of injuring or killing some one else than they were of injuring or killing themselves. If this attitude is an indication of their general preferences, then vehicle manufacturers have hitherto underestimated the demand for non-aggressiveness in their products. As a result, the industry may have over-invested in improving the occupant protection capabilities of the vehicle and under-invested in improving its non-aggressiveness.

Similarly, some of the vehicle safety regulations and policies designed to increase the protection of the occupants may be counter-productive to the safety of non-occupants. When such differences exist, the difference in the perceived role of government will result in different policies, each with drastically different expected outcomes. As an illustration, consider the increasing trend in Australia for consumers to purchase either a small car or a four-wheel drive/sports utility vehicle (Attewell et al [2]). In a crash between a small car and a four-wheel drive (4WD), the 4WD will inflict great damage on the small car but it will suffer little damage. If the focus of policy makers is on occupant protection, they may encourage the consumption of 4WDs and discourage the consumption of small cars. On the other hand, if the focus is on the non-aggressiveness of the vehicle, then policy makers should instead encourage the consumption of small cars. This policy choice, nevertheless, has drastically different safety implications. If there is a greater number of small cars on the road, then a relatively larger portion of the crashes will be between these types of vehicles resulting in a lower fatality rate whereas a larger share of 4WD on the road will result in a higher fatality rate. In addition, the fatality risks of pedestrians, cyclists and motor-cyclists will also be reduced by having a higher proportion of less aggressive vehicles.

---

* Associate Professor in Road Safety, Centre for Accident Research and Road Safety, Queensland University of Technology, Carseldine, Qld 4034, Australia. Tel: 61-7-3864 4806; fax: 61-7-3864 4640; email: r.tay@qut.edu.au.

[1] Sunday Mail, 10/9/200, p114; Courier Mail, 31/8/2000, p3; 18/8/200, p3; 29/7/2000, p13.

Prisoners' Dilemma and Vehicle Safety

This situation creates the classic prisoners' dilemma problem in game theory, which will be further illustrated using the results of Attewell et al [2]. The authors investigated the relative driver fatal injury risk between passenger vehicles of various sizes and part of their results is summarised in Table 1.[2] To illustrate the hypothesis that bigger vehicles are not necessarily safer, we will focus on the two extreme vehicle sizes.[3] In a frontal collision between two small cars, the relative fatality risk of both drivers is 0.8 whereas the relative driver fatality risk is increased to 1.0 if both vehicles are 4WDs. In collision between a small car and a 4WD, the relative driver fatality risk for the driver in a small car is 17.0 while the risk for the driver in the 4WD is only 0.06.

Table 1
Relative Driver Fatality Risk

	Small Car	Medium Car	Large Car	4WD
Small Car	(0.8, 0.8)	(3.6, 0.28)	(6.3, 0.16)	(17.0, 0.06)
Medium Car	(0.28, 3.6)	(1.7, 1.7)	(2.3, 0.44)	(9.0, 0.11)
Large Car	(0.16, 6.3)	(0.44, 2.3)	(1.9, 1.9)	(8.0, 0.13)
4WD	(0.06, 17.0)	(0.11, 9.0)	(0.13, 8.0)	(1.0, 1.0)

When considering buying a vehicle, the consumer for whom occupant protection is a major issue will always prefer to buy a 4WD to a small car because it is the dominant strategy.[4] If the consumer driving a small car hits another small car, his relative chance of a fatal crash is 0.8 whereas if he is driving a 4WD, his odds are reduced to 0.06. Thus, the consumer is better off driving a 4WD if he hits a small car. Similarly, if the consumer hits a 4WD with a small car, his relative risk of a fatal crash is 17.0 whereas his relative risk of a fatal crash in a 4WD is only 1.0. Again, the consumer is better off driving a 4WD. Therefore, regardless of what the other person drives, the consumer is always better-off in a 4WD, making it the dominant strategy. Since the game is symmetric, the other driver will also choose to drive a 4WD. In equilibrium, *other factors being equal*, both consumers will buy 4WDs. This strategy will lead to the outcome given in the lower right-hand box, which is inferior to the outcome on the upper left-hand box - the classic prisoners' dilemma problem. In trying to protect themselves, consumers will choose the outcome (both driving 4WDs) that will ultimately cause more harm to themselves (when compared the outcome where they both choose to drive small cars).

Escape from the Prisoners' Dilemma: Non-Aggressiveness versus Occupant Protection

Similarly, in trying to protect the motorists, policy makers may implement countermeasures that will inflict greater harm on the motorists. To correct this problem, policy makers should instead promote the virtues of having a non-aggressive vehicle, to the extent of *making it dominant over the demand for occupant protection*. For example, the results of vehicle crash tests should place more emphasis on the "likelihood of killing or seriously injuring some one" and less emphasis on the "likelihood of being killed" in a crash while driving a particular vehicle.[5] Also, vehicle design standards should place *greater* emphasis on making the vehicle less aggressive to non-occupants. If the re-education campaign is successful then the consumers' choice will be guided *more* by the non-aggressiveness of the vehicle and *less* by its occupant protection.

Again, returning to the prisoners' dilemma game, the consumer for whom non-aggressiveness is a major factor determining vehicle choice will always prefer to buy a small car to a 4WD because it is the dominant strategy. If the consumer driving a small car hits another small car, his relative chance of killing the other driver is 0.8 whereas if he is driving a 4WD, his odds are increased to 17.0. Thus, the consumer is better off driving a small car if he hits a small car. Similarly, if the consumer hits a 4WD with a small car, his relative risk of killing the other driver is 0.06 whereas his relative risk of killing the other driver increased to 1.0 if he was driving a 4WD. Again, the consumer is better off driving a small car. Therefore, regardless of what the other person drives, the consumer is always better-off in a small car, making it the dominant strategy. Since the game is symmetric, the other driver will also choose to drive a small car. In equilibrium, *other factors being equal*, both consumers will buy small cars. This strategy will lead to the outcome given in the upper right-hand box, which is superior to the outcome on the lower right-hand box - escape from the prison!

---

2 Attewell et al [1] provided data on frontal and side impact crashes but for the purpose of this paper, it is sufficient to examine only frontal crashes.

3 The prisoners' dilemma game produces similar results for the choice between a small car and a medium car or a large car.

4 For simplicity, we will assume that the purchase decision and driving decision is the same and interchangeable.

5 Even though some information on aggressivity was provided in the last column of the latest buyer's guide to used car safety ratings in Australia, occupant protection information took up the entire first five columns of the guide.

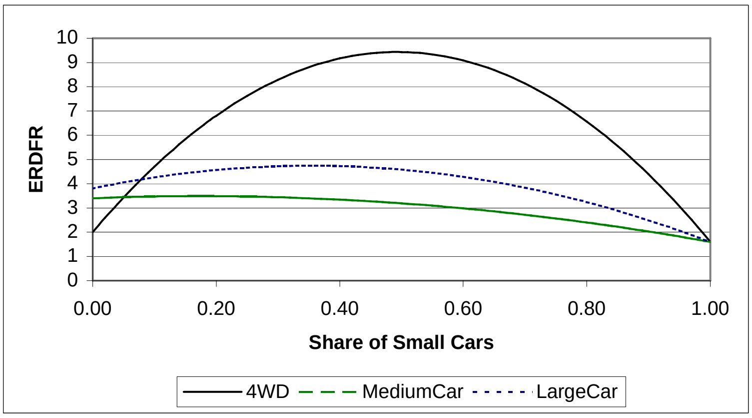
Minimising Road Trauma

It is clear from the above analysis that the extreme case where all drivers choose to drive small cars is clearly superior to the opposite outcome where all choose 4WD - *bigger is thus not necessarily safer*. The interesting question then is whether there exists a mixed strategy equilibrium that is superior to the pure strategy equilibrium. Suppose the consumer chooses to buy a small car with probability α and chooses to purchase a 4WD with probability $(1-\alpha)$. At the aggregate level, this mixed strategy undertaken by the consumer is equivalent to having a vehicular mix on the road with a proportion α of small cars and it can be used to find the optimal mix of vehicle types that will minimise the *overall* road trauma. For simplicity, we will assume that the probability of occurrence for each category of accident is dependent only on the relative proportion of each type of vehicles in the population. The Expected Relative Driver Fatality Risk (ERDFR) can then be calculated for different proportion (α) of small cars in the vehicle population.

(1) $ERDFR_{4W} = (\alpha)(\alpha)[0.8 + 0.8] + 2(\alpha)(1-\alpha)[17.0 + 0.06] + (1-\alpha)(1-\alpha)[1.0 + 1.0]$
$= 2 + 30.12\alpha - 30.52\alpha^2$

As shown in Figure 1, the ERDFR function is quadratic with a unique maximum at $\alpha = 0.49$ and an absolute minimum at the boundary where $\alpha = 1$. The optimal mix that will minimize overall road trauma is a vehicle population with only small cars and the worst distribution is one where the proportion of small cars is slightly less than half.

Figure 1
Expected Relative Drive Fatal Risk



To further illustrate the proposition that bigger vehicles are not safer, we will derive the ERDFR for the small car relative to both the medium and large car categories. Let β be the proportion of small cars relative to medium cars and γ the corresponding proportion relative to the large cars. The respective ERDFRs are as follows:

(2) $ERDFR_M = (\beta)(\beta)[0.8 + 0.8] + 2(\beta)(1-\beta)[3.6 + 0.28] + (1-\beta)(1-\beta)[1.7 + 1.7]$
$= 3.4 + 0.96\beta - 2.76\beta^2$

(3) $ERDFR_L = 3.8 + 5.32\gamma - 7.52\gamma^2$

Again, these functions are quadratic with unique maximums at $\beta = 0.17$ and $\gamma = 0.35$ and an absolute minimum value at the boundary where $\beta = \gamma = 1$.

Several features of the graphs shown are worth noting. First, the vehicle population with only small cars ($\alpha = \beta = \gamma = 1$) has the minimum expected road trauma. This is because the relative driver fatality risk is the lowest for collision between two small cars. The exact numbers in Table 1 are not crucial to this conclusion, only the relative ranking of the risk between collisions involving different types of vehicles is. As long as the collision between small cars has the lowest fatality risk, it will be the preferred choice in minimising the *overall* road trauma in a two-vehicle crash. Second, the larger the incompatibility between two vehicle class (more extreme values on the off-diagonal terms in the table), the greater the curvature of the graph. This implies that mixing vehicles of these types will produce higher risks of fatality. Third, for any two types of vehicle (for example, small car and 4WD), if the sum of the two terms in an off-diagonal entry (17.0 + 0.06) is larger than the main diagonal term (0.8 + 0.8 or 1.0 + 1.0), it is always better to have only one type of vehicle. The safer vehicle type corresponds to the one with a smaller value in the main diagonal (0.8). Last, graphs using either medium car, large car or 4WD as the basis for comparison will produce similar results. The absolute minimum will still occur when ($\alpha = \beta = \gamma = 1$).

Attewell et al [2] also provided the relative number of crashes between vehicles of different types used in his sample.[6] For this particular distribution, the Observed Relative Driver Fatality Risks is given by ORDFR = 34(1.6) + 35(3.88) + 61(6.46) + 21(17.06) + 10(3.4) + 39(2.74) + 11(9.11) + 27(3.8) + 21(8.13) + 1(2) = 1,408.97. However, if all vehicles were small cars, then the ORDFR would fall to 416. This would correspond to a reduction of 70.5% in the ORDFR. Since 226 drivers were killed in the 260 crashes analysed, this reduction in the ORDFR could be translated into a saving of 160 lives. On the other hand, if all vehicles were 4WDs, then the ORDFR would fall to 520, corresponding to a reduction of 63.1% in ORDFR and a saving of 142 lives. The respective savings for medium and large cars were 37.3% and 29.9% or 84 and 67 lives.

It is clear from the above analysis that incompatibility between vehicle types increases road trauma, a result that is well accepted in the literature. More importantly, however, the above analysis also shows that bigger vehicles are not necessarily safer. In fact, among the pure strategy equilibria, the one with only small cars produced the least road trauma because they produced minimum damage to both occupants and non-occupants (other drivers) and thus minimised the *overall* trauma on the road.

Safest Car in a Mixed Fleet

It is also clear from the above analysis that the exact contribution to the overall road trauma by each category of vehicle will depend on their relative share in the population or their relative involvement in the crashes. Even though the pure strategy equilibrium with only small cars produces the least overall trauma, it is unlikely that it or any other pure strategy equilibrium (only one type of vehicle) can be obtained in reality. It is important therefore to know which type of vehicle will produce the greatest road trauma in a mixed fleet. To obtain a fair comparison, we will assume that all crash types in Table 1 are equally likely and there is one crash of each type.[7] The contribution by the 4WD to the ORDFR is 36.3 ($ORDFR_{4WD}$ = 0.06 + 17 + 0.11 + 9.0 + 0.13 + 8.0 + 1.0 + 1.0) and the respective contributions to the ORDFR for the small, medium and large cars are 29.00, 19.13 and 21.13.[8] Therefore, *all things equal*, the 4WD will produce the greatest road trauma in crashes and the medium car produce will produce the least. Again, bigger vehicles are not necessarily safer.

In another recent study, Newstead et al [3] estimated logistic regression models using crash data from the Australian states of Queensland, New South Wales and Victoria. The authors provided estimates of crashworthiness and aggressivity ratings of severe injury risks for different models of vehicles.[9] The respective average (non)-crashworthiness ratings for 4WDs, large, medium and small cars are 23.280, 23.455, 23.330 and 24.382 and the corresponding aggressivity ratings are 21.109, 19.404, 16.103 and 17.032. Using these figures, we can compute a combined rating for overall road trauma which total to 44.389, 42.859, 39.433 and 41.414 respectively for 4WDs, large, medium and small cars. Again, the 4WD will produce the greatest overall road trauma in crashes and the medium car will produce the least, reaffirming our hypothesis that bigger vehicles are not necessarily safer.

The above results are intuitively appealing because the overall road trauma caused by a particular vehicle depends not only on the fatality risk of the driver but also on its ability to inflict mortal injury to the other driver. Even though the 4WD provide the best occupant protection, it is also the most likely to kill the other driver, resulting in a very bad overall rating. The medium sized car, on the other hand, provides the driver with an acceptable level of protection but inflicts only a relatively small damage to the other driver, thus earning itself the title of the "safest car".

---

6 In the derivation of the ERDFRs, we assumed that the probability of occurrence for each category of accident is dependent on only the relative proportion of each type of vehicles in the population. Thus, crash frequency is also directly related to the relative of share of vehicle types.

7 All crash types are equally likely is a requirement for a fair comparison and will result in equal number of crashes of each type. The assumption of one crash per type is made for simplicity in computation. Any equal number across types will produce the same result.

8 Scores obtained by adding the numbers in either the row or column for the respective vehicle.

9 A larger number for the crashworthiness rating and aggressivity indicates a higher level of trauma for the vehicle owner and the other driver respectively. The authors also provided ratings for injury risks and composite score but not ratings for fatality risk alone.

Conclusion

Current vehicle safety regulations in most countries tend to focus more on occupant protection and less on non-aggressiveness. This misplaced emphasis has led to the misconception that bigger vehicles are safer and may have contributed to the inefficiencies in resource allocation in the vehicle manufacturing industry and the road safety sector. Using the relative driver fatality risk and the crashworthiness and aggressivity ratings for severe injury for different types of vehicle in Australia as an example, we demonstrated that bigger vehicles were not necessarily safer when viewed from the perspective of overall road trauma inflicted. The safest car is one that provides the driver with an acceptable level of protection but inflicts only a relatively small damage to the other driver. Consequently, government regulation should place *relatively more* emphasis on improving the non-aggressiveness of the vehicle, making it dominant over increasing occupant protection, even though *the latter is also important*. Arguably, this will then result in a safer environment for all road users, including the vehicle drivers themselves.

Acknowledgment

Support from the Motor Accident Insurance Commission of Queensland is gratefully acknowledged but the views expressed by the author do not necessarily reflect those of the commission.

References

1. Tay R., 1999, College students' perception of the effects of the anti drink driving advertising campaign and the minimum legal drinking age law on road safety in New Zealand. Paper presented at the *21st Conference of the Australian Institutes of Transport Research*, Brisbane, Australia.

2. Attewell R., McFadden M. and K. Seyer K., 1999, *Vehicle compatibility: Analysis of fatal crashes.* Report submitted to the Federal Office of Road Safety, Australia.

3. Newstead S., Cameron M. and Le M., 2000, *Vehicle crashworthiness and aggressivity ratings and crashworthiness by year of vehicle manufacture: Victoria and NSW crashes during 1987-98, Queensland crashes during 1991-98.* Report no. 171, Monash University Accident Research Centre, Melbourne, Australia.