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# Can a road safety measure be both effective and ineffective at the same time? A game-theoretic model of the effects of daytime running lights

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## ABSTRACT

Studies that have evaluated the effects on accidents of daytime running lights for cars have consistently found that cars using daytime running lights are involved in fewer multi-party accidents in daylight than cars not using daytime running lights. However, studies evaluating the effects of mandatory use of daytime running lights have not always found an accident reduction. Although findings are mixed, there is a tendency for the aggregate effects of daytime running lights (i.e. the effects of an increasing share of traffic using daytime running lights) to be smaller than the intrinsic effects (i.e. the difference in accident involvement between cars using and not using daytime running lights). This paper presents a game-theoretic model to explain these apparently inconsistent findings. The game-theoretic model is based on so called Schelling-diagrams, originally introduced by Nobel laureate in economics Thomas C. Schelling. The effects of daytime running lights are modelled by means of Schelling diagrams. It is shown that it is by no means impossible for cars using daytime running lights to always be safer than cars not using daytime running lights, while the total number of accidents remains constant even if the percentage of cars using daytime running lights increases from, say, 10 percent to 90 percent.

Key words: daytime running lights, game theory, Schelling diagrams, effects

## 1 INTRODUCTION

Studies that have evaluated the effects on accidents of daytime running lights (DRL) for cars have been subject to several critical analyses and summaries, see, for example Theeuwes and Riemersma (1995), Elvik (1996) Koornstra et al. (1997) and Elvik et al. (2003). While the majority of researchers interpret studies as showing that the use of daytime running lights on cars is associated with an accident reduction, full consensus has not been reached and concern remains regarding the effects on motorcycle conspicuity of cars using daytime running lights (Cavallo and Pinto 2012).

There are three anomalies in the results of studies that have evaluated the effects on accidents of daytime running lights for cars that have not been fully explained in previous reviews of these studies:

1. There is a clear time trend in the results of studies that have evaluated the intrinsic effects of daytime running lights for cars. Intrinsic effects refer to the effect on the accident involvement of each car by using daytime running lights. The most recent studies indicate far smaller effects than older studies; see Table 1 in Elvik et al. (2003).
2. There is no dose-response pattern with respect to the effects of an increasing use of daytime running lights in a country; see Figure 7 in Elvik et al. (2003). In other words, an increase in the share of cars using daytime running lights from e. g. 30 to 90 percent is not associated with a greater change in the number of accidents than an increase in the share of cars using daytime running lights from e. g. 80 to 90 percent.

3. Not all studies that have evaluated the effects of laws requiring the use of daytime running lights (DRL-laws) find an effect on accidents. On the contrary, the methodologically best evaluation studies find no change in the number of accidents associated with DRL-laws. An example is the most recent Danish evaluation study (Hansen 1995).

Can these anomalies be explained? This paper argues that they are consistent with a game-theoretic model of the effects of daytime running lights as stated in terms of Schelling-diagrams. This model offers an alternative interpretation of the findings of studies that have evaluated the effects on safety of DRL. It should be stressed, however, that the game-theoretic reading of the DRL-literature presented in this paper is only intended to show an alternative perspective on this literature. It is not claimed that it is the only possible interpretation of DRL-studies.

## 2 GAMES MODELLED BY SCHELLING-DIAGRAMS

Schelling-diagrams (Schelling 1978) are used to model binary choices that have external effects. A binary choice is a choice between two options. The choice made will have impacts not just on those who make the choice, but on others as well. To explain how to understand a Schelling-diagram, an example is given in Figure 1.

***Figure 1 about here***

Figure 1 shows the benefits of vaccination as a function of the percentage of the population who vaccinate. The benefits of vaccinating are shown by the upper line. These benefits are assumed to be a linear function of the share of the population who vaccinate and reach maximum when everybody is vaccinated. Vaccination, however, also benefits those who do not vaccinate, i.e. it has positive external effects. These effects are shown by the lower line, which shows the benefits of vaccination for those who do not vaccinate. The external benefits of vaccination for an individual who does not vaccinate increase as the share of the population who vaccinates increases, up to the point where everybody except one individual has vaccinated. The total external benefits of vaccination depend on the share of the population who has vaccinated and reach their maximum when about 75 percent of the population are vaccinated. The rest of the population are then so well protected that it might not be necessary for them to vaccinate. This is indicated by the dashed line in Figure 1.

## 3 INTERNAL AND EXTERNAL IMPACTS OF USING DAYTIME RUNNING LIGHTS

Daytime running lights have positive internal effects and negative external effects. Each vehicle using daytime running lights becomes more conspicuous and thus easier to see. This would be expected to reduce accident involvement. On the other hand, vehicles not using daytime running lights become relatively less conspicuous. This is particularly the case when a high share of vehicles uses daytime running lights. Road users may then come to rely on the sight of lights as a clue for identifying a vehicle and may therefore be less able to identify vehicles that do have their daytime running lights on.

These effects have been shown experimentally. Hole and Tyrrell (1995) studied how quickly a motorcycle was detected depending on whether its headlights were lit or not. Two experiments were conducted. In the first experiment two groups of participants were shown 24 pictures of a motorcycle. In one group the participants were shown 23 pictures of a motorcycle with its headlights off, followed by a 24$^{th}$ picture of a motorcycle with its headlights on. Reaction time to the 24$^{th}$ picture was compared to the mean reaction time to the previous 23 picture. The other group was shown 23 pictures of a motorcycle with its headlights on and then a 24$^{th}$ picture of a motorcycle with its headlights also on. Reaction time to the last picture was again compared to the previous 23 pictures.

In both these cases, the mean reaction time to the 24$^{th}$ picture was shorter than to the other 23. For the group that saw pictures of motorcycles with headlights off, this shows that when headlights are on, detection is quicker. For the group that saw pictures of motorcycles with headlights on, it shows that consistent exposure to headlights is not associated with an erosion of the gain in reaction time brought about by lit headlights. In Figure 2, these results have been converted to percentage changes in reaction time.

***Figure 2 about here***

The data point on the left represents a 4 percent use of daytime running lights (1 out 24 using DRL). Reaction time was shortened by about 14 percent. The data point to the right represents 100 percent use of daytime running lights (24 out of 24). Even then, reaction time to the last picture was shorter than to the previous 23. The two data points located at the bottom of the diagram are based on experiment 1.

In the second experiment, subjects were shown 25 pictures of motorcycles. In one of the series 15 pictures showed a motorcycle with headlights on, 10 showed a motorcycle with headlights off. This was intended to simulate 60 percent use of headlights. Following the 25 pictures, subjects were shown a picture of a motorcycle with headlights off. Reaction times were compared as in the first experiment. In a second series of pictures, 24 out of 25 pictures showed a motorcycle with headlights on. This simulated 96 percent use of headlights. The 26$^{th}$ picture showed a motorcycle with headlights off. Figure 2 shows the percentage difference in reaction time to the last picture compared to the previous 25 for these two experimental conditions. The two upper data points in Figure 2 are based on experiment 2.

It is seen that reaction time to a motorcycle with headlights off increases when 60 percent or 96 percent of motorcycles have headlights on. This shows the negative external effects of daytime running lights. Other studies (e. g. Brouwer et al. 2004) have compared the conspicuity of motorcycles to cars, in order to determine if cars with lit headlights can mask motorcycles without lit headlights. Such a comparison was, however, not relevant in the study by Hole and Tyrrell, since all pictures showed motorcycles exclusively.

## 4 SCHELLING-DIAGRAM OF DRL-EFFECTS

Based on the study of Hole and Tyrrell (1995), Figure 3 shows a Schelling-diagram of the effects of daytime running lights.

***Figure 3 about here***

The lower curve shows the relative accident rate for cars using DRL. It has been assumed that using DRL is associated with a safety benefit. This safety benefit is largest when the share of cars using DRL is low. Cars using DRL will then stand out from the crowd and clearly be more visible than other cars. However, as long as few cars use DRL, road users cannot rely on the sight of headlights to identify a car. The negative external effect will therefore hardly be noticeable. As the share of cars using DRL increases, the safety benefit becomes smaller, but it never disappears. The negative external effect on cars not using DRL becomes larger. When the percentage using DRL becomes very high, the negative external effects may become larger, as road users start to use the sight of headlights as a clue for identifying cars. The shape of the lower curve is based on the findings of evaluation studies, see below. The upper curve, in particular at high levels of DRL-use, is less known. However, once the use of DRL reaches 100 percent, one should expect the negative external effect to disappear.

The curves in Figure 3 have been drawn so that changes in the use of DRL will not have an effect on the total number of accidents. The total number of accidents is indicated by the thick dotted horizontal line located between the risk curves for cars with and without DRL. It is of course not a logical necessity that the curves should look like this. The presence of negative external effects of DRL does not necessarily imply that a net gain in safety cannot exist. However, the shape of the curves in Figure 3 shows that it is not logically impossible for a safety measure to be both effective and ineffective at the same time. Cars using DRL will always have a lower accident rate than cars not using DRL. It is still possible that an increasing use of DRL will not have an effect on the number of accidents, if the negative external effect of DRL exactly balances the favourable internal effect.

## 5 REVIEW OF ANOMALOUS FINDINGS IN DRL-STUDIES

All studies that have compared the accident involvement of cars using DRL to the accident involvement of cars not using DRL have found that cars using DRL are less involved in accidents. This finding is perfectly consistent. It is rarely the case in road safety evaluation research that a finding is reproduced with perfect consistency. The studies reviewed by Elvik et al.(2003) were reported between 1965 and 2003. During this period, there was a clear tendency for the effects attributed to DRL to become smaller. Figure 4 shows this tendency.

***Figure 4 about here***

While the first study indicated that DRL reduced accident involvement by more than 40 percent, recent studies suggest an accident reduction of about 5 percent. A second-degree polynomial best fits the trend in study findings.

How could it be the case that DRLs are less effective now than almost 50 years ago? Surely, vehicle technology has improved considerably in this period. One might therefore expect modern dedicated DRL-lamps to be more effective than the parking lights used as daytime running lights in the early studies. But an altogether different hypothesis is possible: The earliest studies of DRL were made in a traffic system where hardly any vehicles were using DRL. Thus, the few that were, would be standing out from the crowd. More recent studies were made in a traffic system where using DRL was, if not universal, then at least not uncommon. As shown by the model in Figure 3, supported by the study presented in Figure 2, the effects of DRL are expected to become smaller as DRL becomes more common, perhaps reaching their minimum when about half of the cars are using DRL, half are not. In such a situation, one still cannot rely on the sight of headlights to identify a car. However, cars with DRL will already be masking cars without DRL, forcing road users to make an extra effort. This will minimise the difference in safety between cars using DRL and cars not using it.

Studies of laws requiring the use of DRL or campaigns designed to promote their use have not found a clear dose-response relationship between increased use of DRL and changes in the number of accidents. Figure 5 is based on results from nine countries (Elvik et al. 2003). The studies are admittedly of somewhat varying quality; yet if a clear dose-response relationship existed, it ought to have been evident in the figure.

***Figure 5 about here***

No clear dose-response relationship is evident in Figure 5. This is consistent with the game-theoretic model suggesting that an increase in the share of cars using DRL will not necessarily be associated with changes in the total number of accidents.

Finally, not all studies that have evaluated the effect on accidents of laws requiring the use of DRL have found an accident reduction. The quality of these studies vary, but the two Danish evaluations (Hansen 1993, 1995) attained a quality score of 0.86 on a scale ranging from 0 to 1. The data used in these two studies partly overlaps. In the most recent of the two studies, no effect on accidents of the DRL-law could be detected (there was a statistically non-significant reduction of 0.4 percent). Again, this result – which admittedly is different from what the majority of studies evaluating DRL-laws have found – is consistent with the game-theoretic model presented in Figure 3.

## 6 DISCUSSION

Research about daytime running lights has a history of nearly fifty years. It had a promising start with two experiments (Cantilli 1965, 1970) which found large effects of daytime running lights. However, since then research has become less conclusive and not entirely without anomalous findings. One could argue that the anomalous findings highlighted in this paper are exceptions from the main pattern. It might be argued that such exceptions are to be expected, given factors like randomness in accident counts, incomplete accident reporting and the difficulties of doing well-controlled studies of laws that are introduced all over a country. This is a valid point. It is rarely the case that the findings of road safety evaluation studies are perfectly consistent or do not contain a single, or a few results, that are outliers or close to being outliers.

However, one could just as well argue that the findings of studies evaluating the effects of DRL are remarkably consistent. As an example, all studies that have evaluated the intrinsic effect of DRL for cars find an accident reduction, and the size of this reduction becomes consistently smaller over time. This pattern is highly consistent, but previous studies (Elvik et al. 2003) have failed to explain why the effect becomes smaller over time. The explanation could be as suggested by the game-theoretic model, but there could also be other explanations. Recent studies are methodologically weak and improvements in vehicle steering and braking may have made their conspicuity less important for avoiding accidents. Likewise, the absence of a dose-response pattern in the relationship between the size of the increase in the use of DRL and the size of the effect on accidents is entirely consistent with what the game-theoretic model predicts.

None of these observations show that the game-theoretic model introduced in this paper is actually correct or that it is only way to interpret the findings of DRL-studies. It only shows that it cannot be ruled out that a game-theoretic model could be correct. If it cannot be ruled out that this model could be correct, then it also cannot be ruled out that a road safety measure can be both effective and ineffective at the same time.

## 7 CONCLUSIONS

The main conclusions of the research presented in this paper can be summarised in the following points:

1. Three anomalies in the results of studies that have evaluated the effects on accidents of daytime running lights for cars were identified: (a) The intrinsic effects (i.e. the gain in safety for each car by using DRL) have become smaller over time; (b) There is no dose-response relationship between increased used of DRL when it is made mandatory and changes in the number of accidents; (c) Some studies find no effect on accidents of DRL-laws. These anomalies have not been resolved in previous summaries of the DRL-literature.
2. A game-theoretic model of the effects of daytime running lights, stated by means of Schelling-diagrams, is introduced to explain the anomalies.
3. Experimental studies support the plausibility of the game-theoretic model.

4. All the above mentioned anomalies are consistent with the game-theoretic model. This shows that it cannot be ruled out that DRL is a road safety measure that can be both effective and ineffective at the same time.
5. It is not suggested that the main conclusions of previous reviews of DRL-studies are wrong, nor that the model presented here is the v\best explanation of their findings; rather this paper should be seen mainly as offering a new perspective on this literature.

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**LIST OF FIGURES**

Figure 1:

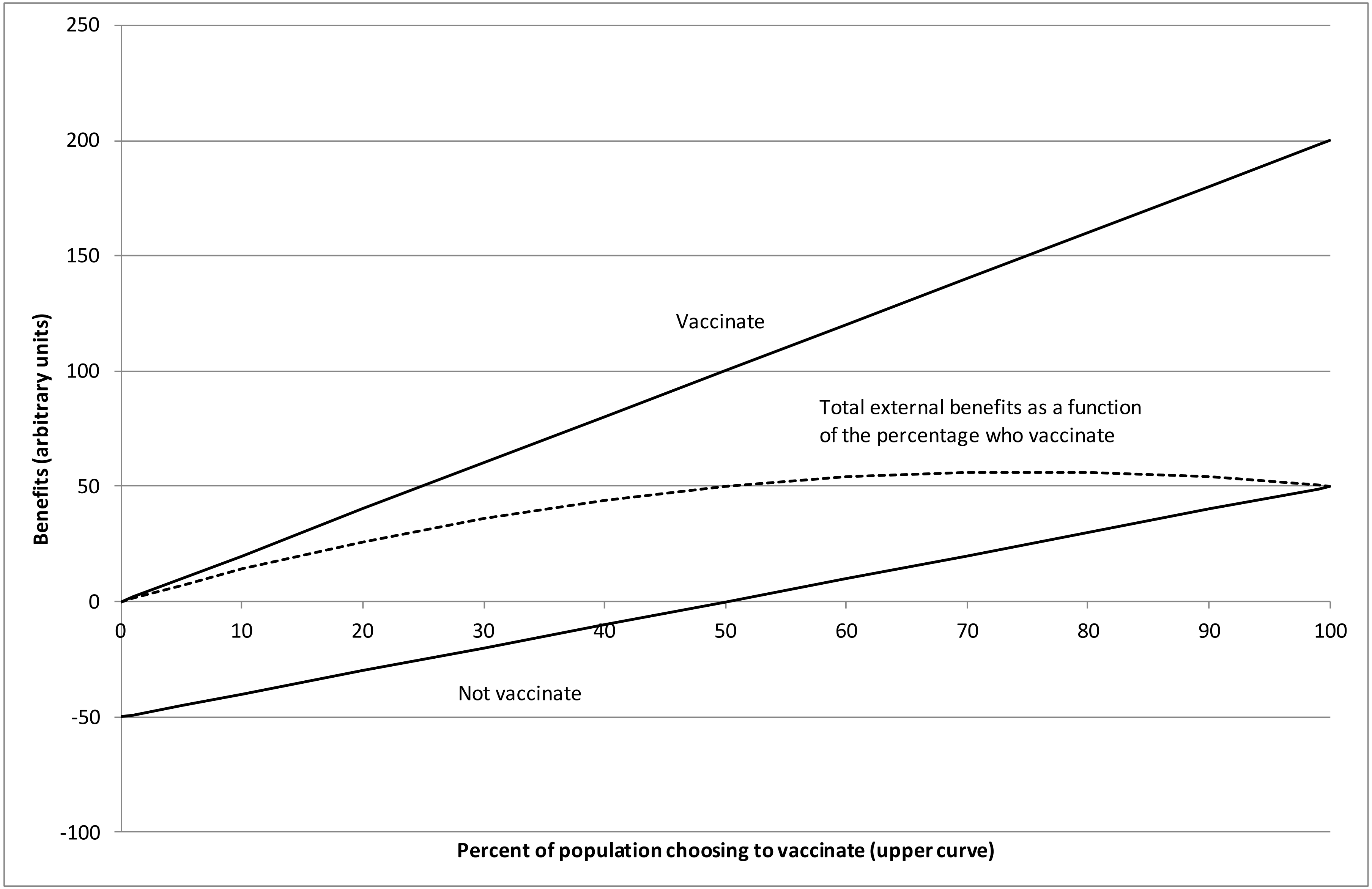
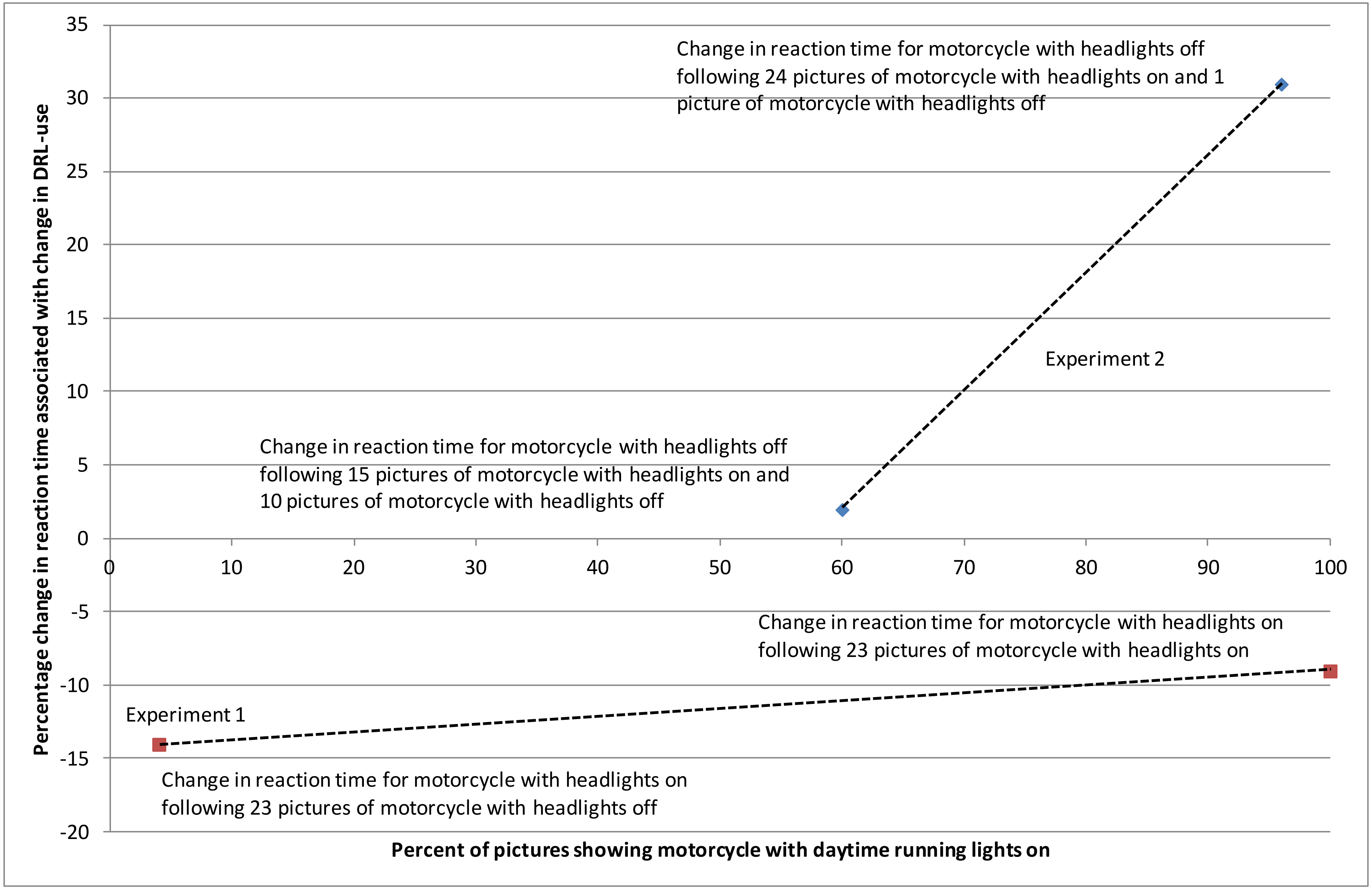

250
200
150
100
50
0
-50
-100
Benefits (arbitrary units)
Vaccinate
Total external benefits as a function
of the percentage who vaccinate
Not vaccinate
0
10
20
30
40
50
60
70
80
90
100
Percent of population choosing to vaccinate (upper curve)

Figure 2:



Change in reaction time for motorcycle with headlights off following 24 pictures of motorcycle with headlights on and 1 picture of motorcycle with headlights off
Experiment 2
Change in reaction time for motorcycle with headlights off following 15 pictures of motorcycle with headlights on and 10 pictures of motorcycle with headlights off
Change in reaction time for motorcycle with headlights on following 23 pictures of motorcycle with headlights on
Experiment 1
Change in reaction time for motorcycle with headlights on following 23 pictures of motorcycle with headlights off
Percentage change in reaction time associated with change in DRL-use
Percent of pictures showing motorcycle with daytime running lights on
35
30
25
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100

Figure 3:

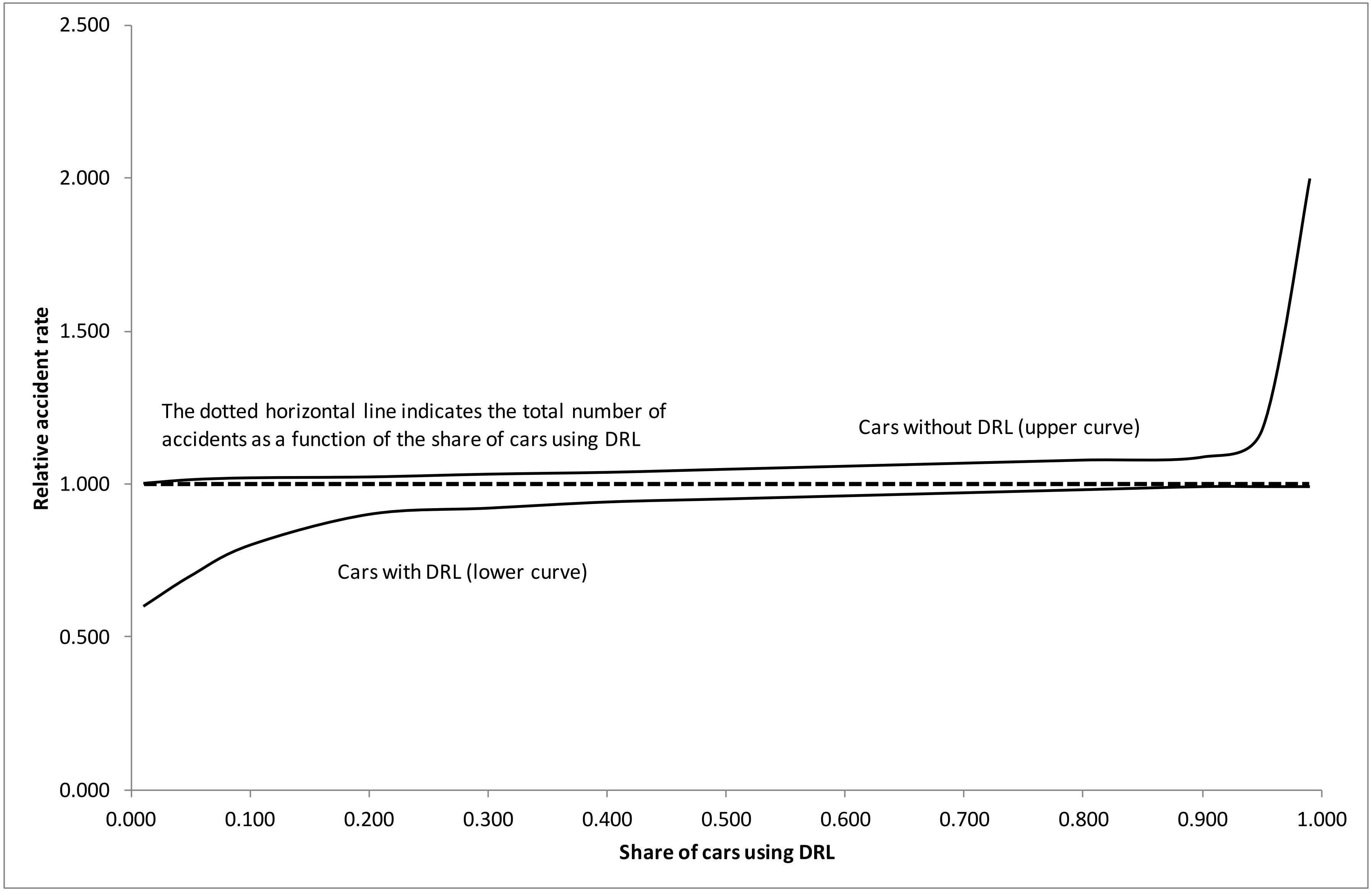
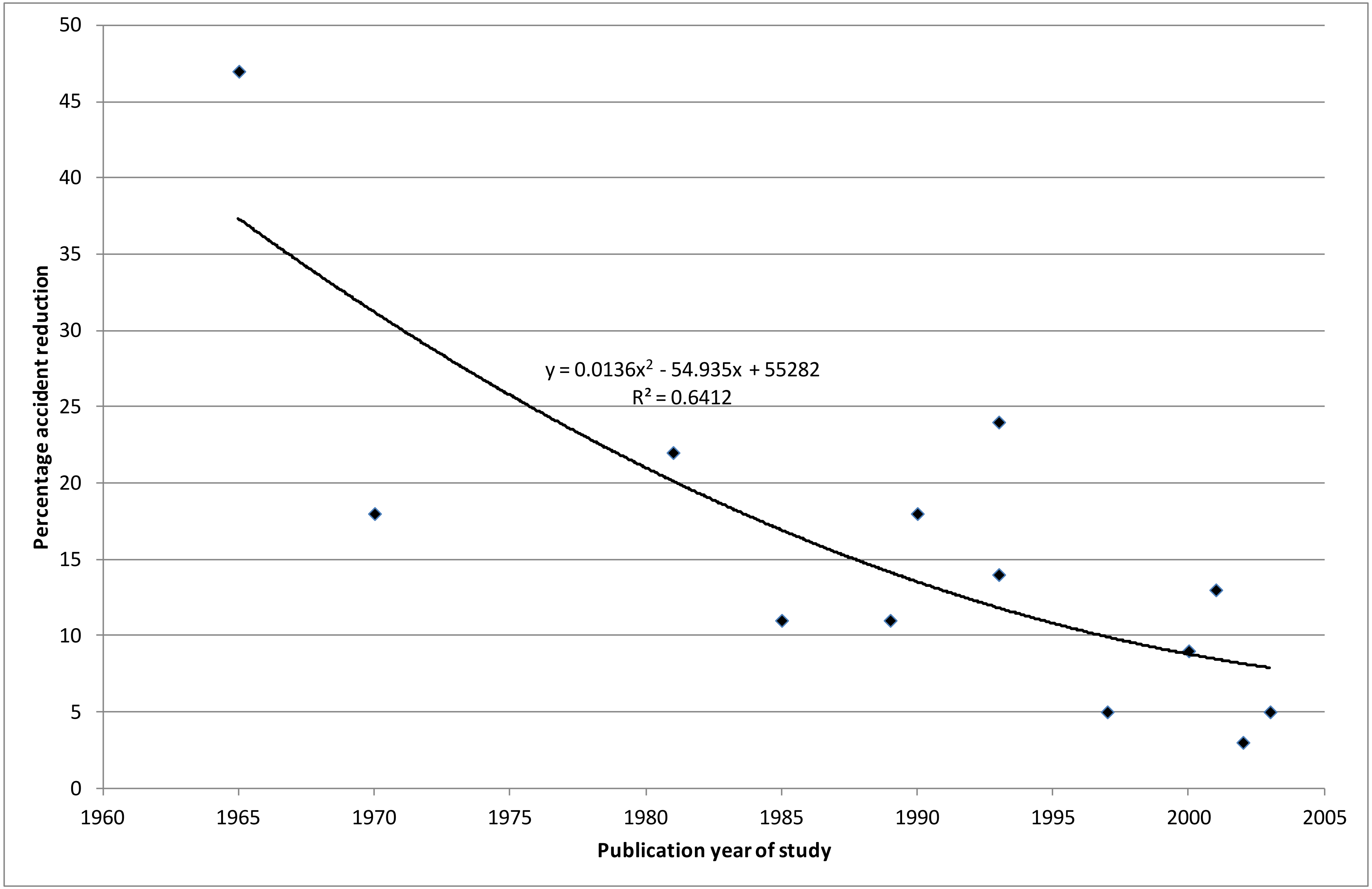
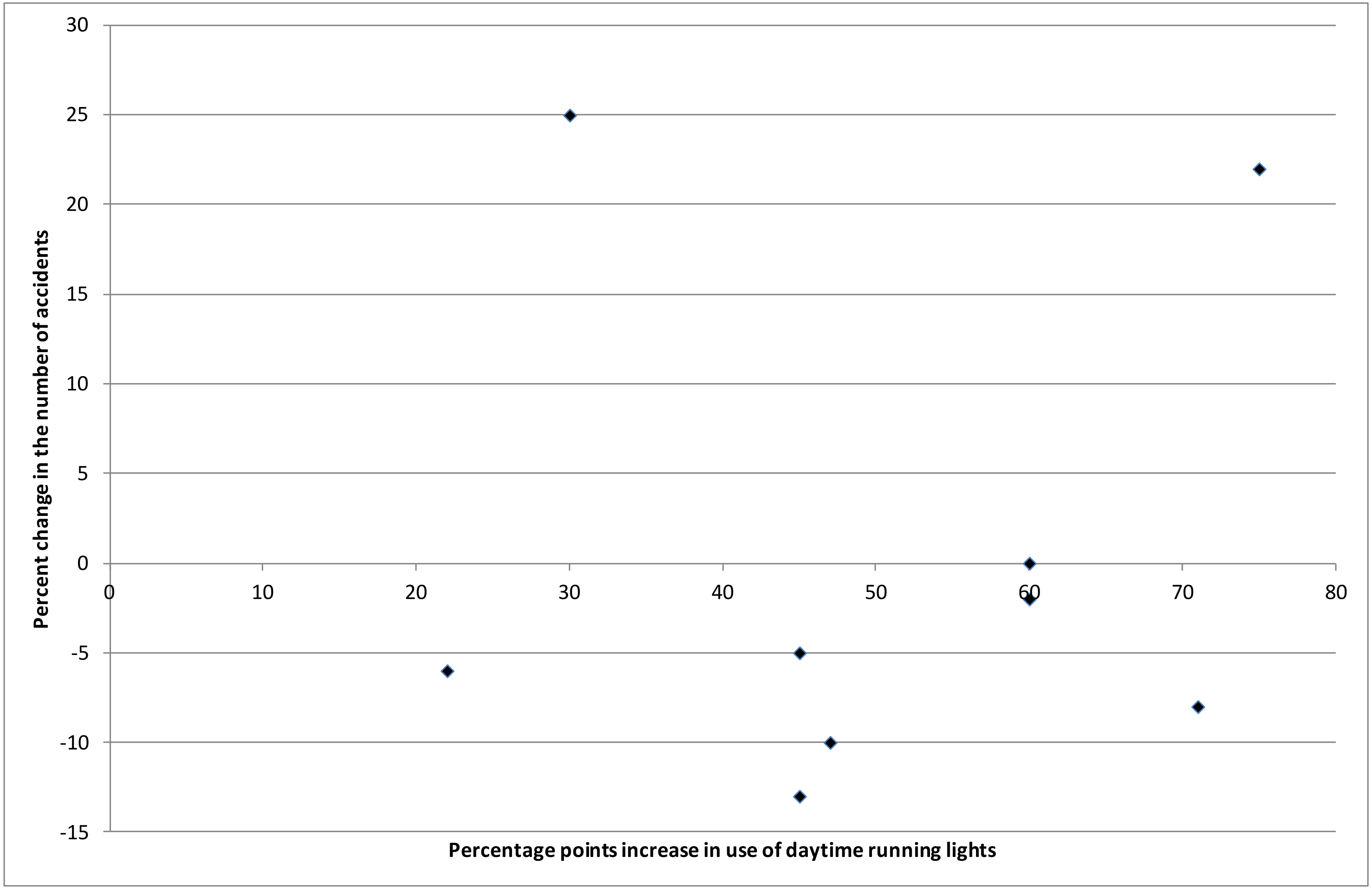

2.500
2.000
1.500
1.000
0.500
0.000
Relative accident rate
The dotted horizontal line indicates the total number of accidents as a function of the share of cars using DRL
Cars without DRL (upper curve)
Cars with DRL (lower curve)
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
Share of cars using DRL

Figure 4:



50
45
40
35
30
25
20
15
10
5
0
Percentage accident reduction
y = 0.0136x2 - 54.935x + 55282
R² = 0.6412
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Publication year of study

Figure 5:


30
25
20
15
10
5
0
-5
-10
-15
0
10
20
30
40
50
60
70
80
Percent change in the number of accidents
Percentage points increase in use of daytime running lights