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# A statistical law in the perception of risks and physical quantities in traffic

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## ABSTRACT

This paper suggests that a universal psychophysical law influences the perception of risks and physical quantities in traffic. This law states that there will be a tendency to overestimate low probabilities or small quantities, while high probabilities or large quantities may be underestimated. Studies of the perception of risk and physical quantities in traffic have found a highly consistent pattern, which shows that:

1. Pedestrians intending to cross the road overestimate the stopping distance of cars travelling at low speed and underestimate the stopping distance of cars travelling at high speed.
2. Car drivers intending to overtake overestimate the distance needed at low speed, but underestimate it at high speed.

3. Car drivers asked to accelerate from standstill to a given speed overshoot the target speed; when asked to slow down to a stated speed, drivers also overshoot the target speed.
4. When asked what speed to choose to save a given amount of time on a trip of given length, driver overestimate target speed when initial speed is low and underestimate it when initial speed is high.
5. Drivers overestimate the increase in risk associated with a small increase in speed and underestimate the increase in risk associated with a larger increase in speed.
6. Drivers overestimate the risk of apprehension for traffic offences when it is low and underestimate it when it is high.
7. Road users overestimate the risk associated with comparatively safe modes of transport and underestimate the risk associated with comparatively hazardous modes of transport.

The paper gives examples of all these misperceptions of physical quantities and risk.

Key words: perceived risk; universal law of subjective probability assessment

## 1 INTRODUCTION

It is widely agreed that the beliefs people have about the outcomes of their actions that determine what they do. To decide if it is safe to cross the road, a pedestrian judges the gap to approaching vehicles by assessing their speed. If a driver believes there is a small chance of getting caught if speeding, he or she may decide to run the risk. Someone who is afraid of flying, may decide to drive instead of flying, although the objective (statistical) fatality rate per kilometre of travel is higher when driving than when flying. If misconceptions of physical quantities like speed or distance or risks associated with choices of behaviour in traffic are widespread, people may choose options that are not in their best interest.

In many contexts, inaccurate perception of physical quantities, probabilities or risks is therefore regarded as problematic. How widespread are such inaccurate perceptions? Does the perception of physical quantities and risks in traffic exhibit predictable statistical regularities? This paper argues that laws of psychophysics, first proposed by Fechner (1860), determine the perception of physical quantities and risks. This implies that the relationship between actual and perceived quantities or risks will have the following characteristics:

1. Small quantities or low probabilities are overestimated.
2. Large quantities or high probabilities are underestimated.
3. The extent to which small quantities or low probabilities are overestimated declines as objective quantity or probability increases.

4. Subjective assessments of quantities or probabilities are compressed, i.e. an event which is, for example, three times as likely as another event will be judged as, for example, twice as likely or 50 percent more likely.
5. Subjective assessments of quantities or probabilities are not well-defined at the extremes. There is a fuzzy region in which the difference between two quantities may be smaller than the just noticeable difference, meaning that they are judged as equal although they are in fact different. By the same token, low probabilities may be treated as zero and high probabilities treated as certainty.

Figure 1 shows the general shape of perceptions conforming to these characteristics. The objective of this paper is to study whether the perception of physical quantities and risks in road traffic conforms to the general pattern indicated in Figure 1.

***Figure 1 about here***

## 2 LITERATURE REVIEW

The first study to demonstrate systematic misconceptions about risk was the now classic study by Lichtenstein et al. (1978) on the judged frequency of lethal events. Lichtenstein et al. obtained data on the actual frequencies of 41 causes of death. They stated the actual frequency of one these causes (for half the sample the frequency of motor vehicle accidents, for the other half the frequency of electrocutions) and asked people to state the frequency of the other 40 causes of death. As expected, the frequency of the stated cause of death influenced the frequencies stated for the other causes of death (an anchoring effect). However, both samples greatly overestimated rare causes of death and underestimated common causes of death. These findings were replicated in a follow-up study published one year after the original study (Slovic et al. 1979).

Kahneman and Tversky (1979), in discussing the shape of the decision weighting function in prospect theory suggest that, in general, low probabilities, rare events, small changes, etc. tend to be overestimated, whereas high probabilities, common events, large changes, etc. tend to be underestimated. They note that several basic characteristics of human perception and memory may contribute to these tendencies. Similar observations are made by Hastie and Dawes (2010), who note that human perception tends to be logarithmic (which was originally suggested by Fechner). A weight of 6 kilograms is felt as distinctly heavier than one of 1 kilograms, but the difference between a sack of potatoes of 27 kilograms and one of 32 kilograms may be less noticed.

Rare events may loom larger in memory than common events. We may remember quite well the air trip when landing was difficult because of a storm, but forget about all the trips involving routine landings in quiet weather. Events that are easily remembered may be judged as more frequent than events that have been partly forgotten or cannot be distinguished from a host of similar events (Tversky and Kahneman 1974).

## 3 PERCEPTION OF PHYSICAL QUANTITIES AND RISKS IN ROAD TRAFFIC

### 3.1 Perception of stopping distance by pedestrians

To decide whether it is safe to cross the road, a pedestrian must assess whether approaching cars are able to stop in time. Sun et al (2015) report a study of pedestrian estimates of the stopping distance of approaching cars. An excerpt of their results is presented in Figure 2.

***Figure 2 about here***

When the actual stopping distance was short, it was considerably overestimated. Pedestrians believing that cars needed a longer distance to stop might reject crossing opportunities that actually are safe. When actual stopping distance is long, it is underestimated. This is clearly more problematic, as pedestrians may then decide to cross when this is actually unsafe.

### 3.2 Perception of overtaking distance by car drivers

Judging distance correctly is decisive when deciding to overtake a car. It is also a difficult task, because an oncoming car will be seen only a rather small object against a background giving few clues about its speed. Gordon and Mast (1968) studied drivers' decisions in overtaking and passing. Drivers were first asked to overtake at different speeds; this part of the study was intended to determine the actual distance needed to overtake. The distance (in metres) needed increased with speed according to a second degree polynomial.

In the second phase of the study, drivers were asked to judge the required overtaking distance at three different speeds. Drivers stated the distance they thought was needed in feet; here this has been converted to metres. Figure 3 shows the results, derived from Figures 5 and 6 in the paper by Gordon and Mast.

***Figure 3 about here***

Short distances were overestimated, long distances underestimated. Thus, drivers might choose to start overtaking when in fact the distance is insufficient to do so. The tendency to underestimate distance was evident at the highest of three speeds (50 miles per hour) used in the study, at which an accident would be more severe than at lower speeds.

### 3.3 Driver perception of speed

Schmidt and Tiffin (1969) studied the perception of speed by drivers who were unable to check actual speed by looking at the speedometer. Four conditions were compared. First, drivers were asked to accelerate from standstill to 40 miles per hour. The mean speed drivers accelerated to was 41.4 miles per hour. Drivers were then asked to accelerate to 70 miles per hour, stay at that speed for five seconds and then slow down to 40 miles per hour. On the average, drivers slowed down to 44.5 miles per hour. In the third condition, drivers accelerated to 70 miles per hour, stayed at that speed for 20 miles (corresponding to 17 minutes) and were then asked to slow down to 40 miles per hour. Drivers, on the average, slowed down to 50.5 miles per hour. This was felt as 40. Finally, in the fourth condition, drivers again accelerated to 70 miles per hour and stayed there for another 20 miles (in addition to the first 20). They were then asked to slow down to 40 miles per hour. The mean speed chosen by drivers was 53.5 miles per hour. Figure 4 shows these results.

***Figure 4 about here***

Drivers' subjective speed scale is a compressed version of the actual scale. A speed reduction of 16.5 miles per hour (from 70 to 53.5) is felt as a reduction of 30 miles per hour (from 70 to 40). In this sense, speed adaptation is an instance of the same statistical law as shown for the perception of distance: speed adjustments based on perceived differences are smaller than ideal adjustments. It is important to note that drivers do not slow sufficiently down after driving for some time at a high speed. This phenomenon, also known as speed generalisation, has been found in studies of how drivers adapt speed following changes in speed limits (Casey and Lund 1992, Sagberg 2006).

### 3.4 Perception of the relationship between speed and travel time

The relationship between speed and travel time for trips of a given distance is very simple. It is an inverse function. If you drive 100 kilometres at 50 kilometres per hour, it will take you two hours. If you double the speed to 100 kilometres per hour, it takes half the time (one hour). Most drivers are likely to have considerable experience in estimating travel time, and one would therefore not expect them to commit systematic errors in doing so. Yet, the errors are pervasive and massive.

Svenson (2009) asked students to estimate changes in speed required to accomplish a certain saving in travel time. For each question, he presented a reference scenario, for example increasing speed from 30 to 40 kilometres per hour when driving a route of 100 kilometres. At the lower speed, the trip will take 3 hours and 20 minutes. At the higher speed, it will take 2 hours and 30 minutes. Thus, increasing speed from 30 to

40 km/h saves 50 minutes. He then asked students what speed they would need to keep if the initial speed was, for example, 60 km/h and the target was to save 50 minutes. Driving a distance of 100 kilometres at 60 km/h will take 1 hour and 40 minutes. To save 50 minutes, you need to complete the distance in 50 minutes, which means you need to increase your speed to 120 km/h. The mean answer given by students was 73 km/h. Figure 5 shows a sample of results.

***Figure 5 about here***

When the stated initial speed was low, the increase in speed needed to save a certain amount of time was overestimated. When the stated initial speed was high, the increase in speed needed to save a certain amount of time was underestimated. Thus, in two samples of students, when actual speed needed to increase to 300 kilometres per hour, mean answers were 88 and 93 kilometres per hour. Engineering students were no better than psychology students in judging the speed needed to save a certain amount of travel time. The message to drivers should be that if are going at 120 kilometres per hour, increasing speed to 130 kilometres per hour will not save much time, whereas increasing speed from 30 to 40 kilometres per hour will save a lot of time.

### 3.5 Perception of accident risk associated with increased speed

It is well-established that increasing speed increases the risk of accident and the severity of injuries (Elvik 2013). In the same study as quoted in section 3.4, Svenson (2009) asked students about the increase in the risk of an injury accident and the risk of a fatal accident they believed was associated with a stated increase in speed. He used the Power model of Nilsson (2004) to describe the actual relationship between speed and accident risk. Figure 6 shows the results for injury accidents.

***Figure 6 about here***

It is seen that at modest increases in speed, the increase in risk is slightly overestimated. It is, however, considerably underestimated at larger increases in speed. Svenson also found that the risk of a fatal accident was not judged to increase more than the risk of an injury accident, which means that the risk of a fatal accident is grossly underestimated.

### 3.6 Perceived risk of apprehension for traffic offences

Studies of the relationship between the subjective and objective risk of apprehension for traffic offences are not an exact science. It is clear that the scale used to determine the subjective risk of apprehension may influence results. Thus, Åberg (1983) compared two scales for subjective risk of apprehension. The first scale asked respondents to state the number of times a driver would be detected out of 365 trips (i.e. one trip per day during a year). The most frequent answers were 0 or 1 (mean 0.691). It was suspected that the scale generated a "floor effect" (a concentration of answers to 0 or 1), because most drivers may have thought that the risk of apprehension was less than 1 in 365. Another scale was therefore tested, asking drivers to state the number of times out of 1,000 that a driver would be caught by the police. Again, however, the most frequent answers were 0 and 1, and the mean number of times stated was 0.831, not very different from the 365 trips scale. Plots show that the distributions of answers were very similar according to the two scales.

Two important lessons from the study by Åberg need to be kept in mind:

1. The scale used to assess subjective risk of apprehension should not be (strongly) affected by floor effects or ceiling effects, i.e. a clustering of most answers at the lower or upper end of the scale.
2. The scale should be directly comparable with a scale for objective risk of apprehension and not rely on transformations that may influence the properties of the scale (such as a log transformation, which will compress the scale).

A number of studies of the subjective and objective risk of apprehension for traffic offences have been reviewed, all of which satisfy the above two criteria. The first study was reported by Glad (1985A). In an evaluation of the effects of a road safety campaign in 1985, he asked a sample of drivers about the number of drivers per 1,000 committing a certain violation that they thought would be caught by the police, when driving on roads close to the location where drivers had been stopped roadside to answer the questionnaire. Possible answers were 0, 1, 2, 3-5, 6-10, 11-20, 21-50 and more than 50. The survey was conducted three times. Since mean answers were virtually identical in the three surveys, mean values have been used. Based on the survey, a comparison can be made between subjective and actual risk of apprehension for drinking and driving (Glad 1985B) and speeding (Sakshaug 1986). The actual risk of apprehension was greatly overestimated for both these offences.

The second study, by Åberg et al. (1986) compared subjective and actual risk of apprehension for drinking and driving. Risk was stated as the number of drivers per 1,000 who would be (believed to be) caught by the police. Based on Figures 1 and 2 of the report, thirteen data points were generated, each representing a combination of values for subjective and actual risk of apprehension.

The third study, by Jørgensen and Pedersen (2005), compared subjective and actual risk of apprehension for speeding on a road near the city of Bodø in Norway. Both estimators of risk were stated as drivers caught per 730 trips, but this was converted to 1,000 trips (= 1,000 drivers) by multiplying by 1,000/730.

The fourth and fifth studies were reported by Elvik (2010) and Elvik and Amundsen (2014). The latter of the two studies was a replication of the first. Actual and perceived risk of apprehension for speeding was compared by asking a sample of drivers (interviewed by phone) how often they thought a driver who was constantly speeding by 15 km/h would be caught by the police. Possible answers were: (1) The first year (scale value 1.00); (2) Within three years (scale value 0.33); (3) Within six years (scale value 0.17); (4) Within ten years (scale value 0.10) and: (5) Never (scale value 0.00). The actual risk of apprehension was computed using an identical scale. To be comparable with other values in this paper, the scale was converted to number of drivers caught per 1,000 drivers by applying data on mean trip length in Norway (Farstad 2014).

The sixth and final study was reported by Ryeng (2012). Drivers were stopped roadside on four major roads in Norway and asked how many hours of police enforcement they thought there was per month on each of the roads. The actual amounts of enforcement were 0 hours per month on two of the roads and 71 and 88 hours per month on the other two roads. The latter two values are extremely high by Norwegian standards. Risk per 1,000 drivers was estimated as:

Risk per 1,000 drivers = $\frac{71}{24 \cdot 30} \cdot 1000$

71 is the number of hours per month of enforcement. Twenty four times thirty is the total number of hours per month. Thus the fraction shows the share of all hours in a month when there is enforcement. This share represents the probability that a driver arriving at random will be caught. Hence, to get the number of drivers caught per 1,000 speeding drivers, the fraction is multiplied by 1,000.

Figure 7 shows the results based on the studies reviewed above. To be able to plot the two data points in the study by Ryeng where actual risk of apprehension was zero, these two data points were assigned nominal values of 0.001.

***Figure 7 about here***

The figure shows the pattern expected according to the statistical law of subjective probability assessment. However, the results of the study by Ryeng (2012) are very influential in producing this pattern. It was the only study producing data points indicating an underestimation of the risk of apprehension (the two data points to the far right in figure 7). It was also the only study producing data points associated with no enforcement (the two data points to the far left in Figure 7). The other data points in Figure 7 are all located above the diagonal (i.e. all indicate an overestimation of the risk of apprehension) and seem to be running parallel to the diagonal. A closer examination of these data points shows that this is not the case.

When the four data points from Ryeng (2012), which are to the far left and far right in Figure 7, are omitted, the pattern shown in Figure 8 emerges for the remaining data points.

***Figure 8 about here***

Figure 8 confirms that there is a tendency, albeit quite noisy, for the ratio of perceived to actual risk to approach 1 as actual risk of apprehension increases.

### 3.7 Perceived risk for different modes of transport

The final example to be given of the statistical regularity in the perception of risk concerns the fatality risk associated with different modes of transport. The study was first presented by Elvik and Bjørnskau (2005). A sample of Norwegians were asked in 2003 about how safe they thought it was to travel by means of airplane, train, car, etc. Answers were stated as: (1) Very safe; (2) Safe; (3) A little unsafe; and (4) Very unsafe. By converting these categories to a numerical scale with values of, respectively, 0.01; 0.1; 1 and 10, a numerical estimate of the subjective risk associated with each mode of transport was developed. The subjective risk associated with the various modes of transport was then converted to a scale where the mode perceived as safest had the value of 1.00. Similarly, statistical estimates of fatality rates per billion kilometres of travel were converted to relative values with the safest mode having the value of 1.00. Figure 9 shows the resulting relationship between actual and perceived risk.

***Figure 9 about here***

It is seen that risk is overestimated for the two safest modes, aviation and rail. For all other modes it is underestimated. Moreover, the range of perceived risk goes only from 1 to about 26 (i.e. the highest perceived risk is 26 times higher than the lowest), whereas the range of actual risk is more than 100. This occurred in spite of the fact that the scale used for coding answers had a range of 1,000.

## 4 DISCUSSION

More than 150 years ago, Gustav Theodor Fechner suggested that human perception of physical quantities was logarithmic. Countless studies of psychophysics, i.e. human perception and assessment of physical quantities have since been made. More recently, cognitive psychologists have suggested that subjective assessments of probabilities or physical quantities are systematically biased in predictable ways (Tversky and Kahneman 1974, Kahneman and Tversky 1979). More specifically the frequency or likelihood of rare events tends to be overestimated and the frequency or likelihood of common events tends to be underestimated. Humans do not take sufficient account of sample size when judging the probability of an outcome; this tendency has been labelled "belief in the law of small numbers".

Are these tendencies found in road traffic? The examples collected and presented in this paper show that they are. A collection of examples, although showing a highly consistent pattern, does obviously not prove that a tendency is universal. Still, the examples given refer to quite different objects, e.g.: distance to a pedestrian crossing; distance to a vehicle approaching in the opposite direction; speed needed to save a stated amount of travel time; fatality rates of different transport modes. Some of these objects are physical, some are abstract. Yet, a similar pattern of misperception appears for all of them.

Are these misperceptions likely to have any impact on road safety? One can easily think that they might have an impact. Thus, pedestrians sometimes reject safe gaps, but accept unsafe gaps. Drivers may overtake when the distance to do so is too short. Drivers may speed excessively in low-speed areas, erroneously believing that they need to do so to save time. Finally, travellers may opt for comparatively unsafe modes of transport, because they think that the safer modes are less safe than they actually are. All these potential impacts are adverse for road safety.

It is nevertheless difficult to believe that the biases in perception exemplified in this paper can be fully corrected, i.e. that people can be taught how to assess distance or speed or risk correctly. Future vehicles may have technology to support drivers in making correct decisions, for example technology informing the driver about whether there is sufficient distance to overtake or about when to brake in order to come to a standstill at a pedestrian crossing. Risks are abstract and exist only as a set of potential outcomes. The risk of an accident is, from any reasonable point of view, so low that informing about it in an easily understandable way is difficult.

## 5 CONCLUSIONS

The main conclusions of the study presented in this paper can be summarised as follows:

1. Subjective assessments of physical quantities and risk are governed by universal mental heuristics that tend to result in an overestimation of small quantities or risks and an underestimation of large quantities or risks.
2. A tendency has been found for:

a. Pedestrians to overestimate short stopping distances of cars and underestimate long stopping distances of cars.
b. Car drivers to overestimate short distances needed for overtaking and underestimate long distances needed for overtaking.
c. Car drivers to insufficiently reduce speed to a given target speed, in particular if driving a longer time at the higher speed.
d. Car drivers to overestimate how much speed must be increased to save a certain amount of travel time when initial speed is low and underestimate the required increase in speed if initial speed is high.
e. Car driver to overestimate the increase in accident risk associated with a small increase in speed and underestimate the increase in accident risk associated with large increase in speed.
f. Car drivers to overestimate a low risk of apprehension for traffic offences and underestimate a high risk of apprehension.
g. Travellers to overestimate the fatality rate of safe modes of transport and underestimate the fatality rate of hazardous modes of transport.

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## LIST OF FIGURES AND TABLES

Figure 8:

Ratio of perceived to actual risk of apprehension as a function of actual risk of apprehension

Figure 9:

Relationship between actual and perceived fatality rate for seven modes of transport

Figure 1:

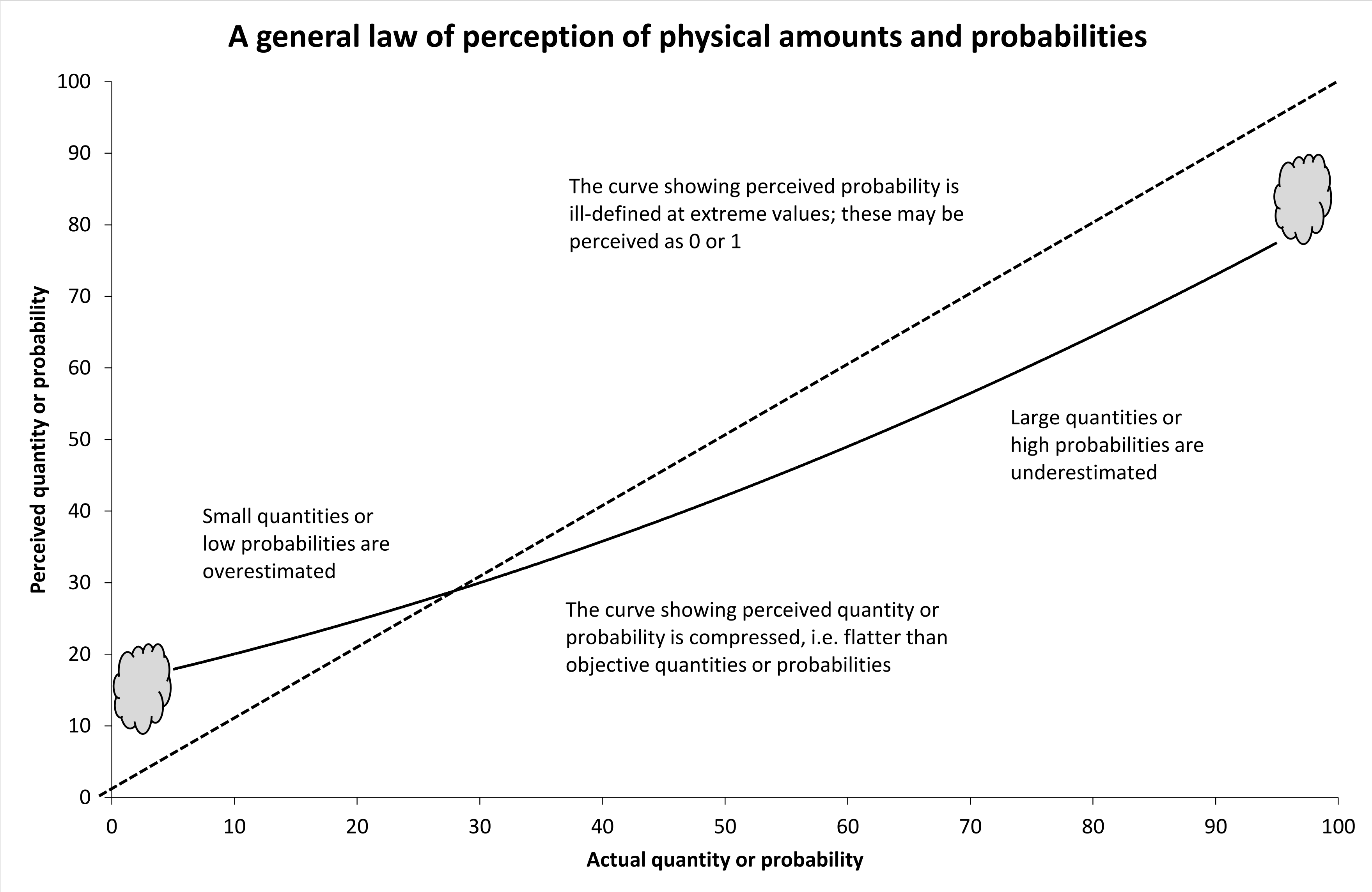

A general law of perception of physical amounts and probabilities
100
90
80
70
60
50
40
30
20
10
0
Perceived quantity or probability
0
10
20
30
40
50
60
70
80
90
100
Actual quantity or probability
The curve showing perceived probability is ill-defined at extreme values; these may be perceived as 0 or 1
Large quantities or high probabilities are underestimated
Small quantities or low probabilities are overestimated
The curve showing perceived quantity or probability is compressed, i.e. flatter than objective quantities or probabilities

Figure 2:

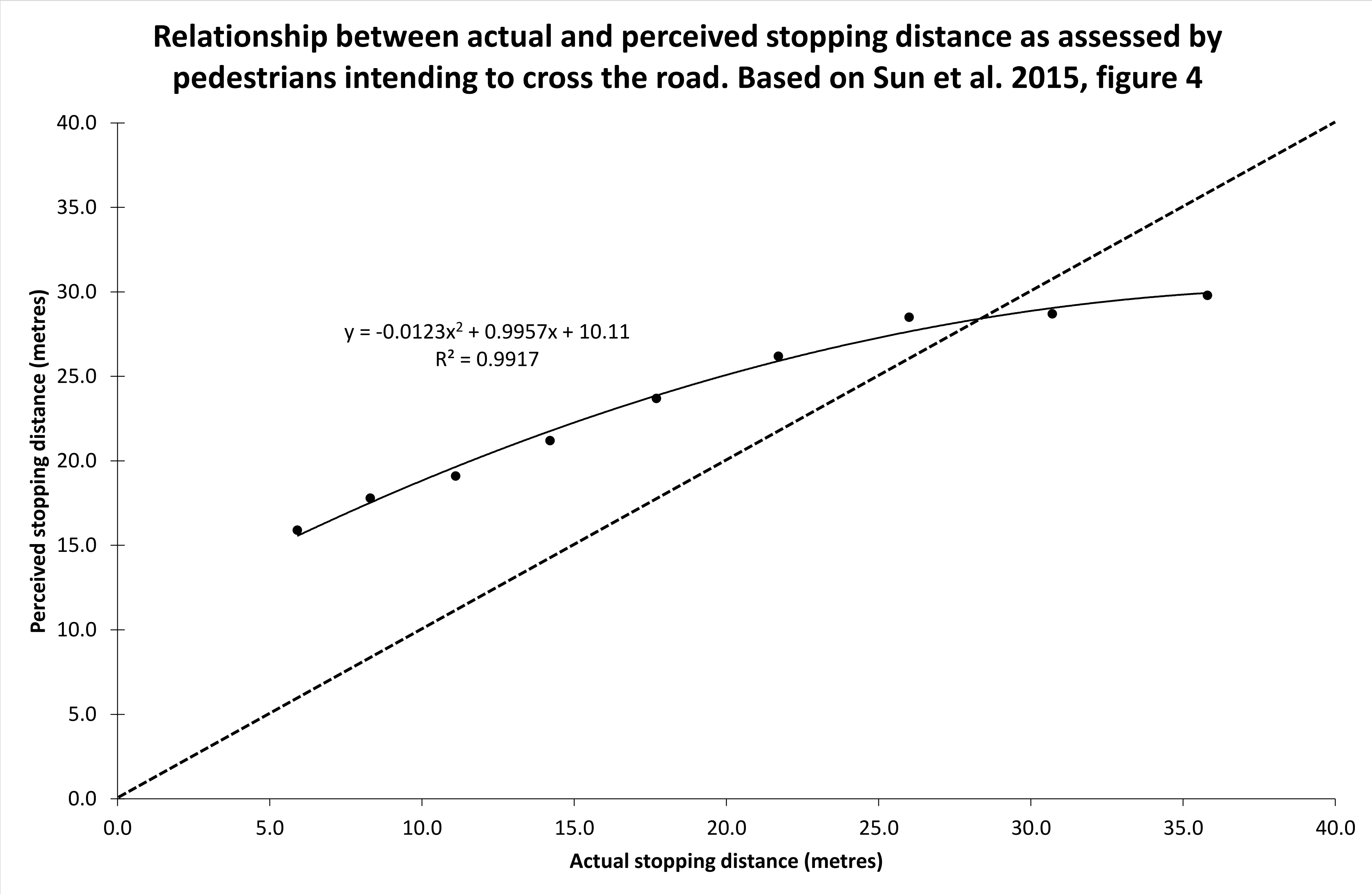
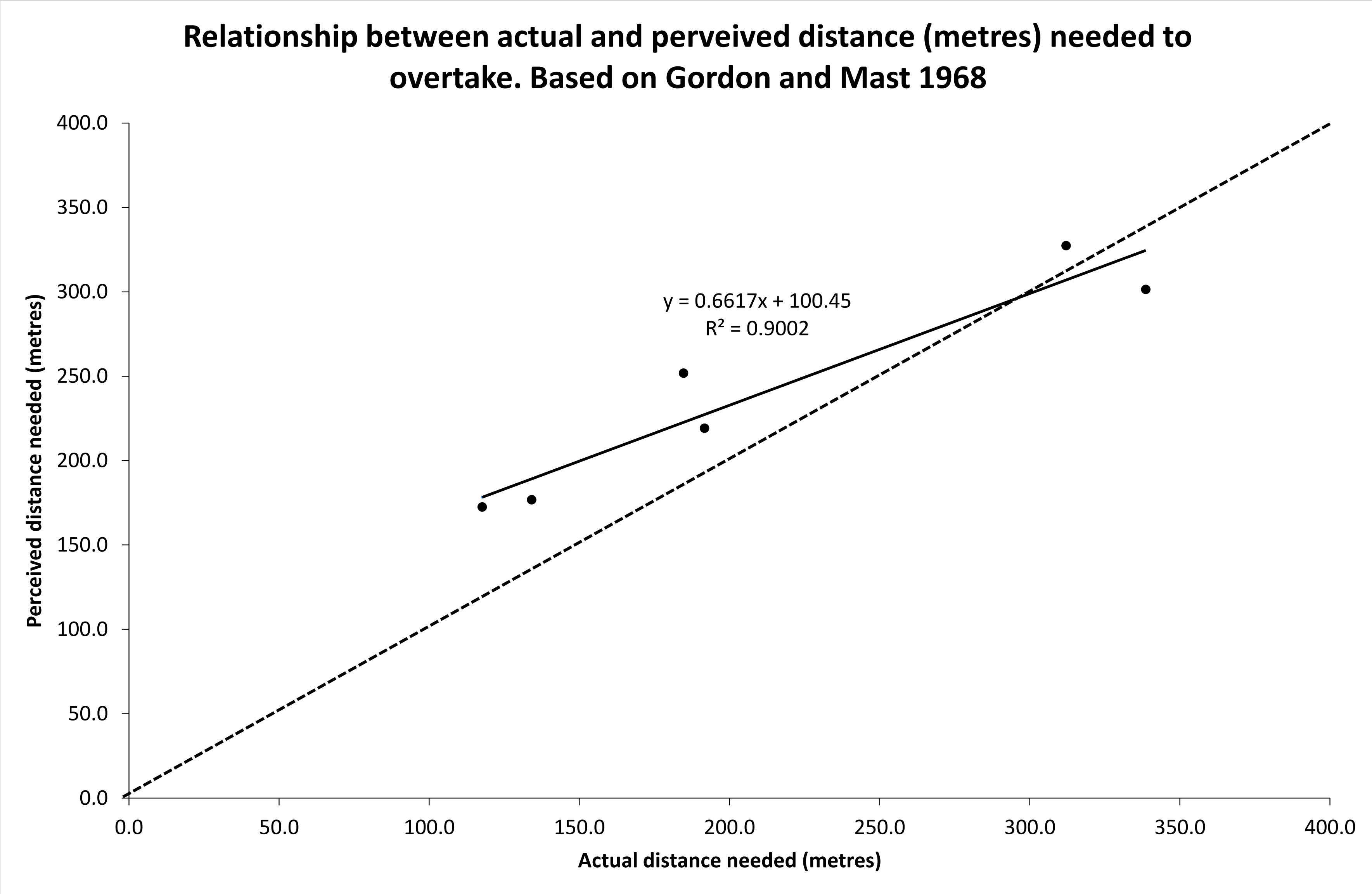
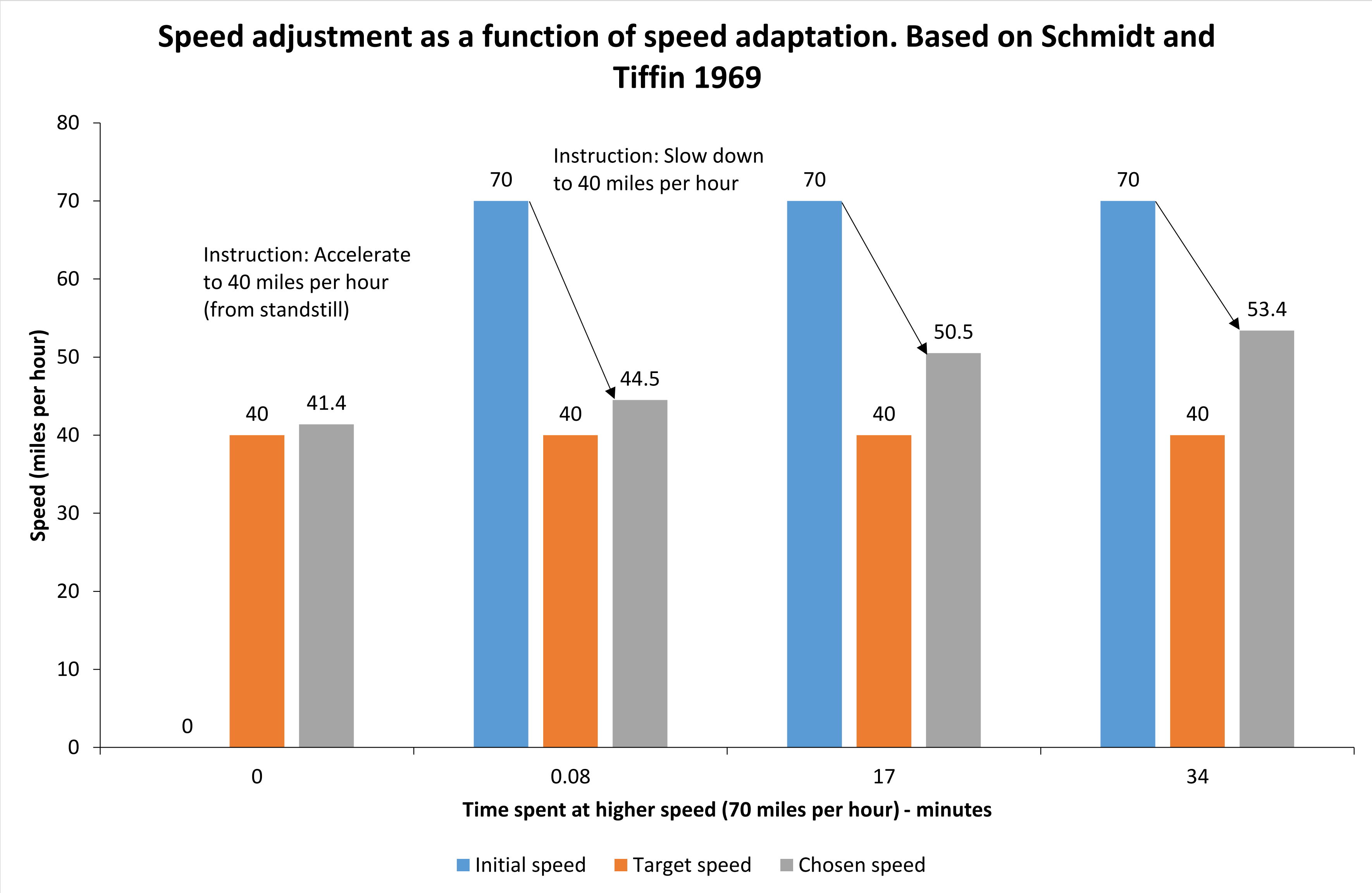

Relationship between actual and perceived stopping distance as assessed by pedestrians intending to cross the road. Based on Sun et al. 2015, figure 4
y = -0.0123x² + 0.9957x + 10.11
R² = 0.9917
Perceived stopping distance (metres)
Actual stopping distance (metres)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0

Figure 3:



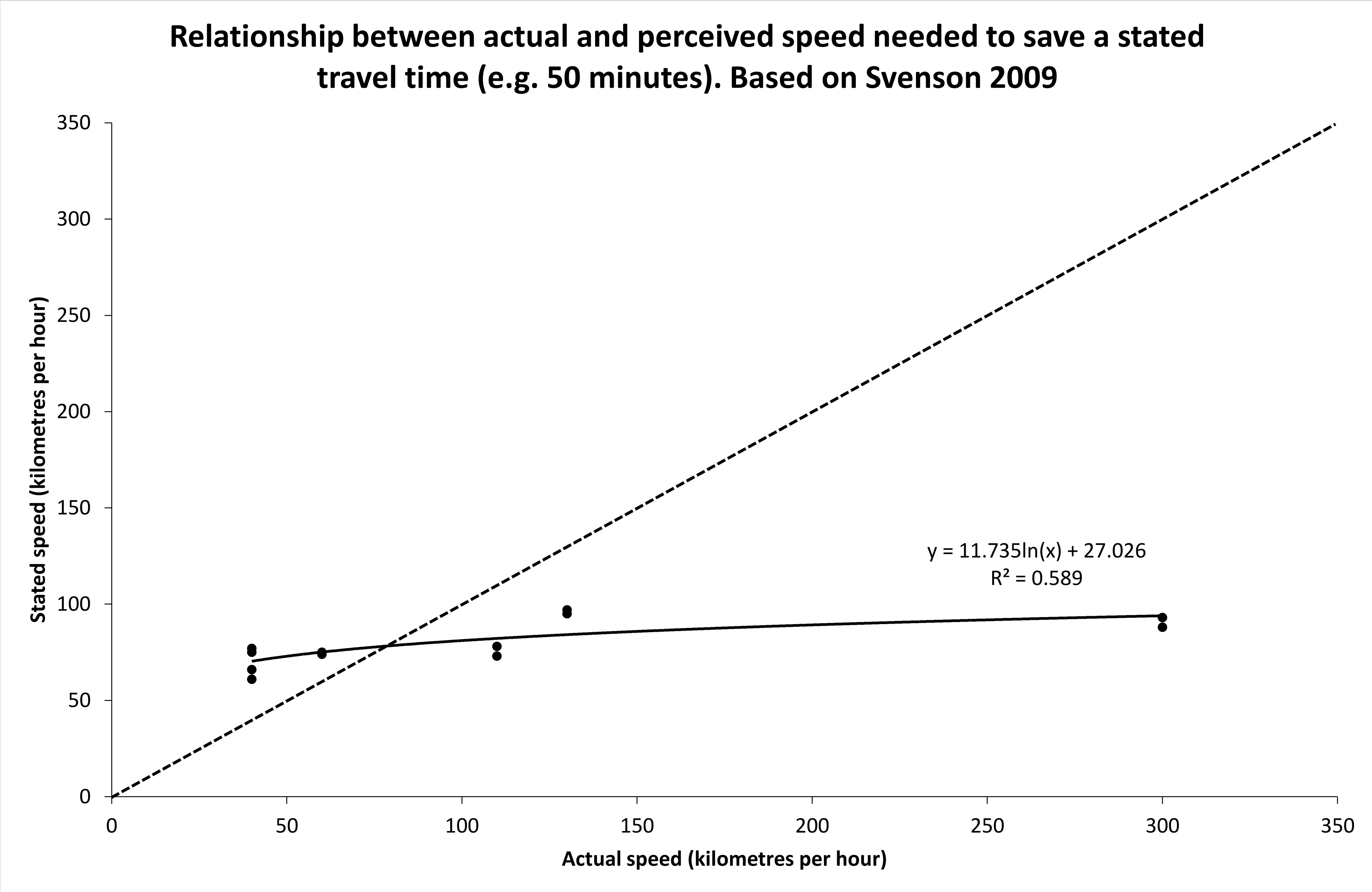
Relationship between actual and perveived distance (metres) needed to overtake. Based on Gordon and Mast 1968
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Perceived distance needed (metres)
y = 0.6617x + 100.45
R² = 0.9002
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
Actual distance needed (metres)

Figure 4:



Speed adjustment as a function of speed adaptation. Based on Schmidt and Tiffin 1969
80
70
60
50
40
30
20
10
0
Speed (miles per hour)
Instruction: Accelerate to 40 miles per hour (from standstill)
Instruction: Slow down to 40 miles per hour
0
40
41.4
70
40
44.5
70
40
50.5
70
40
53.4
0
0.08
17
34
Time spent at higher speed (70 miles per hour) - minutes
Initial speed
Target speed
Chosen speed

Figure 5:



Relationship between actual and perceived speed needed to save a stated travel time (e.g. 50 minutes). Based on Svenson 2009
y = 11.735ln(x) + 27.026
R² = 0.589
Stated speed (kilometres per hour)
Actual speed (kilometres per hour)
0
50
100
150
200
250
300
350

Figure 6:

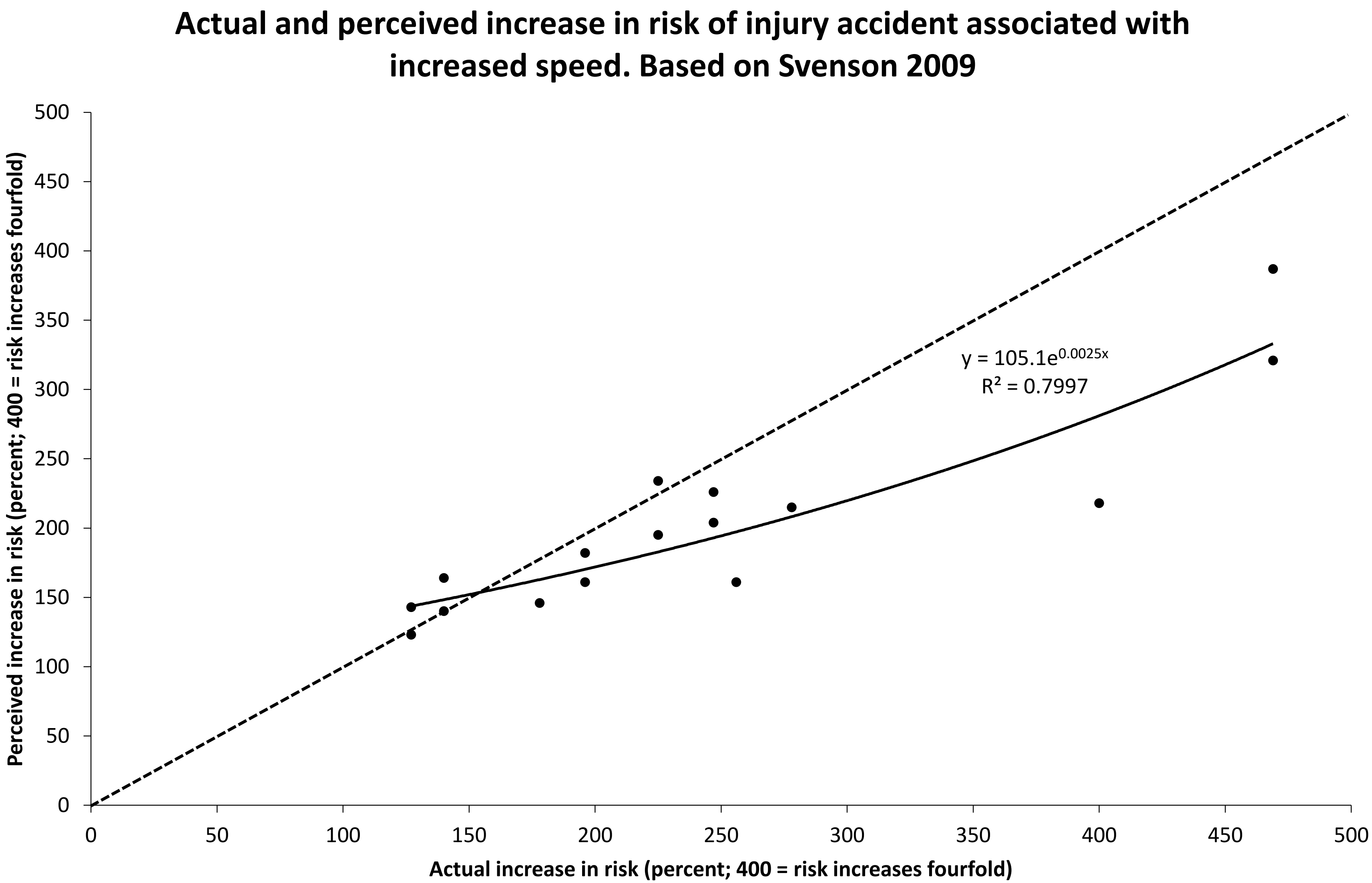

Actual and perceived increase in risk of injury accident associated with increased speed. Based on Svenson 2009
Perceived increase in risk (percent; 400 = risk increases fourfold)
0
50
100
150
200
250
300
350
400
450
500
y = 105.1e^0.0025x
R² = 0.7997
Actual increase in risk (percent; 400 = risk increases fourfold)

Figure 7:

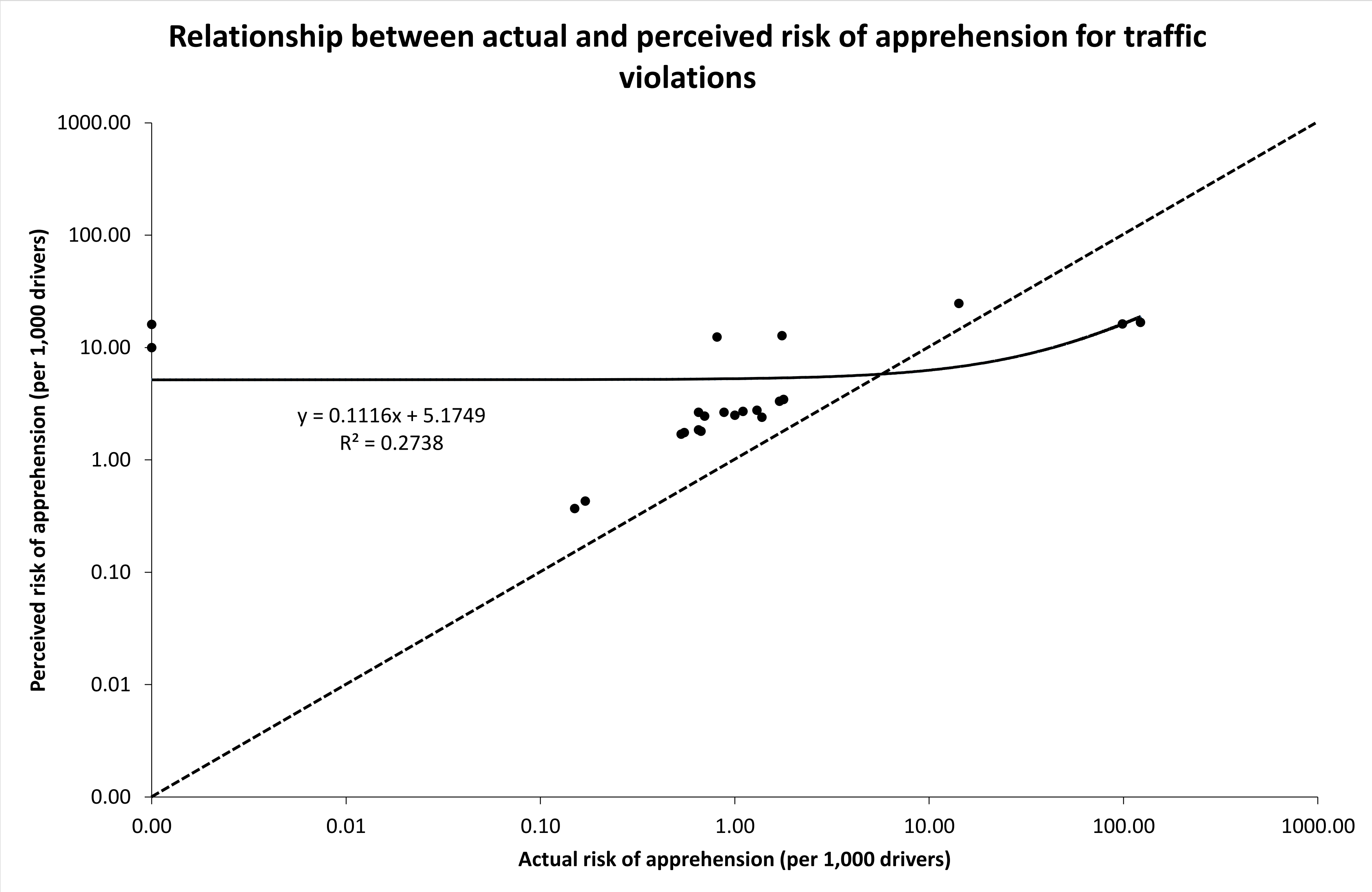

Relationship between actual and perceived risk of apprehension for traffic violations
Perceived risk of apprehension (per 1,000 drivers)
1000.00
100.00
10.00
1.00
0.10
0.01
0.00
y = 0.1116x + 5.1749
R² = 0.2738
0.00
0.01
0.10
1.00
10.00
100.00
1000.00
Actual risk of apprehension (per 1,000 drivers)

Figure 8:

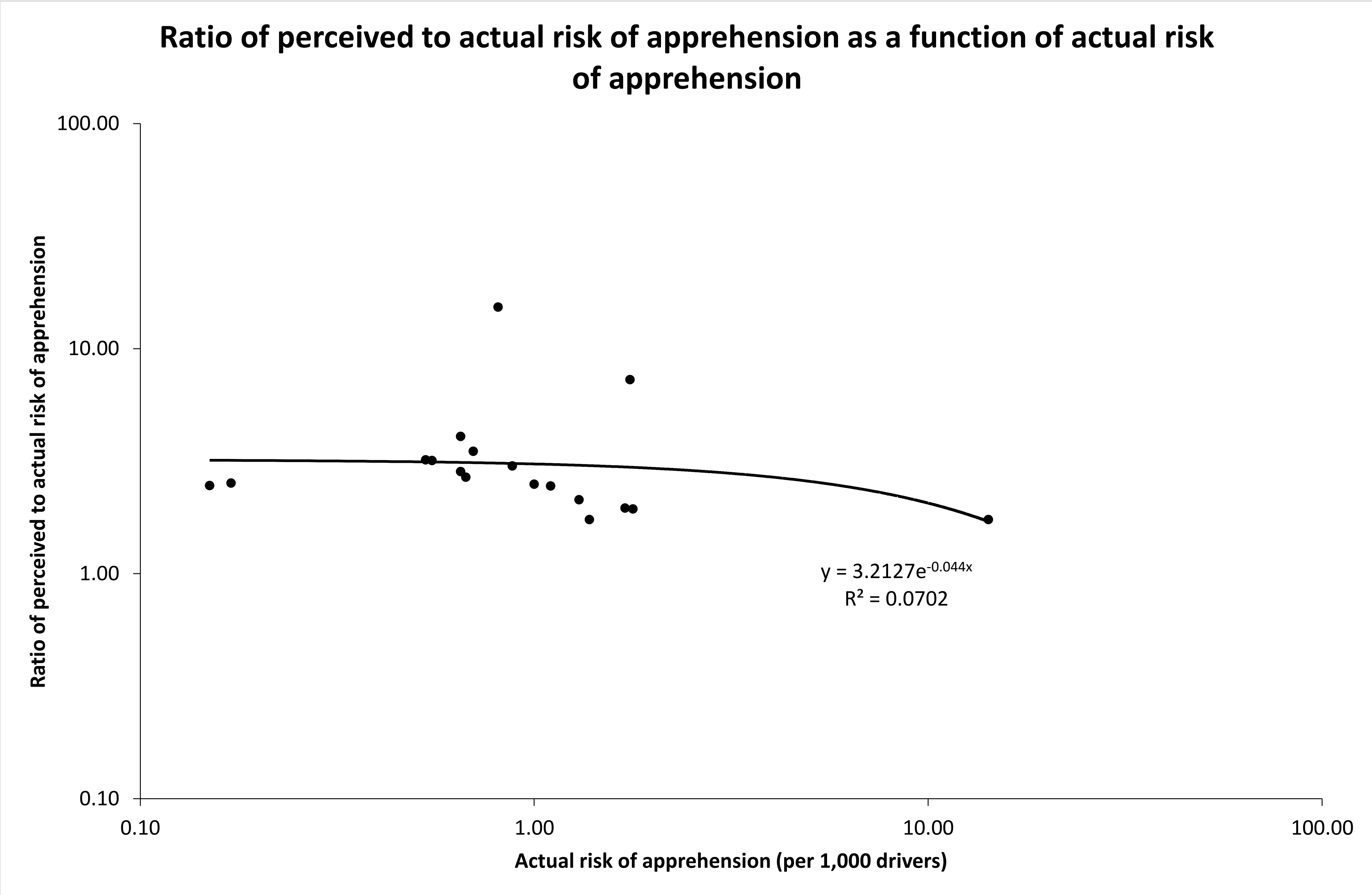
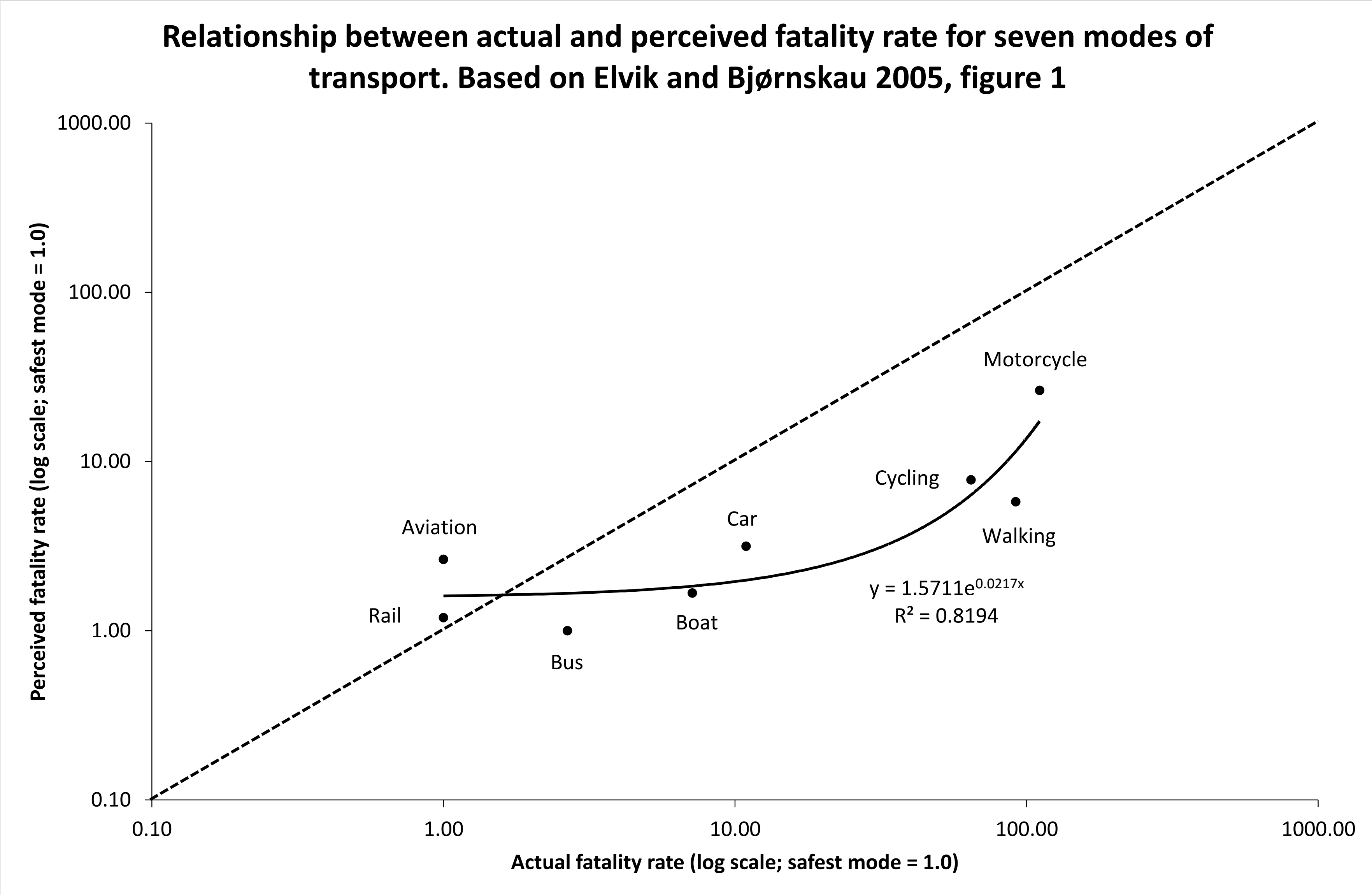

Ratio of perceived to actual risk of apprehension as a function of actual risk of apprehension
100.00
10.00
1.00
0.10
Ratio of perceived to actual risk of apprehension
y = 3.2127e^-0.044x
R² = 0.0702
0.10
1.00
10.00
100.00
Actual risk of apprehension (per 1,000 drivers)

Figure 9:



Relationship between actual and perceived fatality rate for seven modes of transport. Based on Elvik and Bjørnskau 2005, figure 1
1000.00
100.00
10.00
1.00
0.10
Perceived fatality rate (log scale; safest mode = 1.0)
0.10
1.00
10.00
100.00
1000.00
Actual fatality rate (log scale; safest mode = 1.0)
Motorcycle
Cycling
Walking
Car
Aviation
Rail
Bus
Boat
y = 1.5711e^0.0217x
R² = 0.8194