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A comprehensive and unified framework for analysing the effects on injuries of measures influencing speed

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ABSTRACT

This paper proposes a comprehensive and unified framework for analysing the impacts on traffic injury of measures influencing speed. The key tool for analysis is a specification of the speed distribution, which in most cases closely approximates a standard normal distribution. The speed distribution can be represented, for example, by twelve intervals each comprising one half standard deviation. The exponential model of the relationship between speed and the number of injured road users is applied to estimate the expected injury rate for drivers travelling at the mean speed of any part of the distribution. The relationship between individual driver speed and accident involvement is then incorporated into the speed distribution. A speed distribution specified this way represents both the mean speed of traffic and the variation in speed-related risk between drivers. Impacts of changes in speed that can be modelled include: (1) Shifting the whole speed distribution, (2) Compressing the upper end of the speed distribution, (3) Enlarging or reducing the variance of the speed distribution, (4) Selective changes in specific regions of the speed distribution.

Examples are given of how knowledge of the impacts of measures on speed can be translated into expected changes in the number of injured road users by relying on the analytic framework.

Key words: speed; distribution; variance; exponential model; analytic framework

1 INTRODUCTION

Speed is an important risk factor for traffic injury. This applies both to the speed of an individual driver and to the mean speed of traffic (Elvik et al. 2019). Most reviews summarising knowledge about the relationship between speed and traffic injury have focused either on the speed of traffic or on individual driver speed. Few reviews (Aarts and van Schagen 2006, Elvik et al. 2019) have included studies both of individual speed and the speed of traffic. There is a vastly larger number of studies dealing with the speed of traffic than dealing with individual driver speed.

Studies of the relationship between the speed of traffic and road safety focus on the mean speed of traffic only. Based on these studies, changes in the mean speed of traffic can be related to changes in road safety, but characteristics of the distribution of speeds in traffic (e.g. variance, skewness) are ignored.

Studies of the relationship between individual driver speed and accident involvement have traditionally been interpreted as indicating the relationship between speed variance and road safety. Such an interpretation is not unproblematic (Hauer 2004). There are methodological issues in all studies of the relationship between individual driver speed and accident involvement. However, three Australian case-control studies (Moore et al. 1995, Kloeden et al. 1997, 2001) are reasonably well-controlled. Elvik et al. (2019) re-analysed these studies. Exponential models of the relationship between speed and accident involvement were found to best fit the data. When coefficient estimates were combined using the inverse variance technique, the mean value of the speed coefficient was 0.046. This is very close to the weighted mean value of coefficients in exponential models estimated by Elvik (2014) for the mean speed of traffic for fatal, serious and slight injury. Applying the share of injuries that are fatal, serious and slight as weights, the mean value of the coefficients was 0.042.

Based on these results, it does not seem unreasonable to assume that the relationship between individual driver speed and accident involvement has the same shape and strength as the relationship between the mean speed of traffic and the number of injuries. If this assumption is approximately correct, it permits an integration of the micro and macro levels of analysis, by specifying a speed distribution where risk varies depending on speed, i.e. increases as speed increases.

The objective of this paper is to describe a comprehensive and unified framework for analysing the impacts on road safety of measures influencing speed and characteristics of the speed distribution. The framework is comprehensive in the sense that it can be used to analyse the effects of different changes in speed: a uniform reduction of speed in all regions of the distribution; a greater reduction of high speeds than low speeds; a change in the variance of the speed distribution, and a change in the distribution of drivers between different levels of speed. The framework is unified in that it incorporates speed-related between-driver variation in risk into the speed distribution, thus integrating the micro and macro levels of analysis.

2 SPECIFICATION OF SPEED DISTRIBUTION

Speed is a continuous distribution. It is nevertheless convenient to divide it into intervals to facilitate analysis of changes in speed. It will be assumed that speed has a normal distribution. The validity of this assumption is easy to test. Consider, as an example, the distribution of speeds for 830 cars belonging to the control group in the case-control study of Kloeden et al. (2001). This distribution is shown in Figure 1.

Figure 1 about here

The expected distribution of drivers in a normal distribution has been computed and is listed along with the actual distribution. As can be seen, the actual distribution is close to the normal distribution. A Chi-square test found that the actual distribution of drivers by speed differs from a normal distribution (χ^2 = 23.04; df= 10; p = 0.0106). Does this mean that a normal distribution of speed should not be assumed? Not necessarily. Two considerations are relevant.

First, whether the differences between the actual distribution and the normal distribution are systematic or not. A systematic difference would be, for example, that the actual distribution has a tail to one end not found in the normal distribution. The differences seen in Figure 1 are not systematic in this sense. Second, in the interest of generalisation, analysis should rely on a known theoretical distribution, like normal, binomial, lognormal, gamma or any other bell-shaped distribution, and not on an idiosyncratic empirical distribution, which may happen to be different from most theoretical distributions. The issue is therefore if any other theoretical distribution in general fits empirical distributions better than the normal distribution. This is not known to be the case with respect to the distribution of speed. A normal distribution is therefore assumed.

3 INTEGRATING MICRO AND MACRO LEVELS OF ANALYSIS

The normal distribution has been divided into twelve intervals. These span the range from three standard deviations below the mean to three standard deviations above the mean. It is assumed that the entire speed distribution is contained within this range. Mean speed in each interval can be estimated if the mean speed of traffic and its standard deviation are known. Speed data often report mean speed and 85th percentile speed. The 85th percentile is 1.04 standard deviations above the mean. Thus, by taking the difference between the 85th percentile and the mean, and dividing it by 1.04, an estimate of the standard deviation is obtained.

Table 1 shows the speed distribution for roads in Norway with a speed limit of 80 km/h. In 2017, the mean speed of traffic on these roads was 76.1 km/h. For each interval of the speed distribution, the relative rate of fatalities, serious injuries and slight injuries for drivers driving at the mean speed within that interval has been estimated. The relative rate of fatalities and injuries has been set to 1.000 at the mean speed of traffic.

Table 1 about here

The exponential model of the relationship between speed and road safety has been used to estimates the relative rates. The exponential model has been preferred to the power model for two reasons. First, it fits individual driver data better than the power model. Second, it fits better to high-speed data points than the power model, which underestimates the steepness of the relationship between speed and safety at high speeds. Coefficients of 0.08 for fatalities (Elvik et al. 2019), 0.06 for serious injuries (Elvik 2014) and 0.04 for slight injuries (Elvik 2014) have been applied. For a driver in the first interval above the mean, relative fatality rate is:

Relative fatality rate (0-0.5 above mean) = $e^{((77.9-76.1)\cdot 0.08)}$ = 1.155.

Relative rates of serious and slight injuries have been estimated the same way, using the coefficients of 0.06 and 0.04, respectively. The contribution of drivers in each speed interval to the total number of fatalities or injuries is estimated by multiplying relative rate with the percentage of traffic belonging to an interval. For the uppermost interval, the contribution to fatalities becomes: 0.6 · 4.874 = 2.92.

Table 1 is the framework for analyses of changes in speed. In the next section, four examples of analysis are presented.

4 OPTIONS FOR ANALYSIS

Four options for analysis will be presented. The first is a uniform reduction of speed across the entire speed distribution. The whole speed distribution is shifted to the left, as shown in Figure 2. Lowering the speed limit may have an effect resembling this (Vadeby and Forsman 2017).

Figure 2 about here

Table 2 shows how the effect on fatalities of a uniform speed reduction of 6 km/h can be estimated. Relative fatality rates in each interval of the speed distribution are reduced by:

$e^{(-6\cdot 0.08)}$= 0.619 = 38.1 % reduction.

Table 2 about here

These reductions are the same in each interval and for the entire speed distribution. It is seen that reductions of speed above the mean contribute to most of the reduction of the relative number of fatalities.

In the second example, there is a larger reduction of high speeds than of low speeds. This is shown in Figure 3.

Figure 3 about here

A change like the one shown in Figure 3 is sometimes found when speed cameras are installed (Vadeby and Forman 2017). Table 3 shows how the effect on fatalities of the changes in speed are estimated. Relative rates in each speed interval are reduced in accordance with the size of the speed reduction in that interval. The total reduction of fatalities is 29 %, which is more than the change in the mean speed of traffic by itself would suggest:

$e^{(-2.3 \cdot 0.08)} = 0.832 = 16.8$ % reduction

Table 3 about here

The reason for this difference is that when estimating effects for specific regions of the speed distribution, account is taken of the fact that the highest speeds are associated with the highest fatality rates. If only the mean speed of traffic is used, no account is taken of the differences in risk in different parts of the speed distribution.

The third example is a reduction of the variance of the speed distribution. This is actually a somewhat artificial example, as a pure reduction of variance, i.e. a reduction of the spread of the distribution leaving the mean speed unchanged, implies that high speeds are reduced and low speeds increased. Such a change is unlikely to take place in practice. Nevertheless, since the claim has been made (see e.g. Lave 1985) that it is the variance of speed, not its mean value, that matters for safety, an example has been developed. Figure 4 shows the distribution before and after a reduction of variance.

Figure 4 about here

Table 4 shows how the effect on fatalities of the change in variance is estimated. There is a reduced number of fatalities in the upper part of the speed distribution, but an increase in the lower part of the speed distribution.

Table 4 about here

The net effect of reduced variance is a reduction of the number of fatalities of about 8 %. This is fully explained by the fact that risks are higher at high speeds than at low speeds. If risk is constant across the entire speed distribution, decreases in speed at the upper end will be cancelled by increases in speed at the lower end and the net effect will be zero. It is therefore not really variance as such that matters, but a higher risk at higher speeds.

The fourth and final example concern the deterrent effect of police enforcement or an increase in penalties. The effect will be to change the percentage of drivers belonging to each interval of the speed distribution. In the normal distribution, the uppermost interval contains 0.6 % of drivers. If half of them are deterred, the percentage drops to 0.3 %. Those who are undeterred continue to drive at the same speed as before. This has been modelled by assuming that 50 % in the 2.5-3 above interval are deterred, 40 % in the 2-2.5 above interval are deterred, 30 % in the 1.5-2 above interval are deterred, 20 % in the 1-1.5 above interval are deterred, 10 % in

0.5-1 above interval are deterred and 5 % in the 0-0.5 above interval are deterred. These assumptions are not altogether unrealistic (Elvik 2015). The deterred drivers migrate to safe territory, i.e. to the speed intervals 0-0.5 and 0.5-1 standard deviation below the mean speed. Figure 5 shows how these changes affect the speed distribution.

Figure 5 about here

The mean speed changes slightly, from 76.1 to 75.3 km/h. Table 5 shows how effects on fatalities are estimated. All relative risks remain unchanged, it is only the percentages of drivers in each interval of the speed distribution that changes. The overall reduction of the number of fatalities is estimated to be close to 8 %. This is greater than one would predict if only the change in mean speed was known:

$e^{(-0.8\cdot 0.08)}$ = 0.938 = 6.2 % reduction.

Table 5 about here

The explanation is once again that higher speeds are associated with higher fatality risk, so that reducing them contributes disproportionately to reducing the total number of fatalities.

5 DISCUSSION

The framework proposed in this paper allows for a more precise analysis of the expected effects on road safety of measures influencing speed. The framework enables this by specifying a speed distribution and assuming that the risk of fatalities and injuries varies across the speed distribution. Making the latter assumption is reasonable in view of the fact that individual driver accident involvement rate has been found to display the same association with speed as the mean speed of traffic.

This framework for analysis can explain some surprising findings in the literature. Høye (2015), for example, evaluated the safety effects of section control in Norway. Speed data were not available for all sites, but assuming these data were representative of all sites, the change in the mean speed of traffic would predict a 40 % reduction of fatalities and a 31 % reduction in the number of serious injuries. The mean predicted effect for fatalities and serious injuries combined is 33 % reduction. The effect estimated in the study was a 49 % reduction of fatalities and serious injuries. As shown in the example above, the change in mean speed by itself is a bad predictor of the safety effect if high speeds were reduced more than low speeds. In the example, relying on the change in mean speed predicted a fatality reduction of 17 %, whereas estimating effects for the different intervals of the speed distribution predicted a fatality reduction of 29 %.

Unfortunately, most evaluation studies using speed data rely on the mean speed of traffic only. Studies of the relationship between speed and road safety are also based exclusively on the mean speed of traffic and changes in it. The results of these studies vary, even for close to identical changes in speed. Explaining these differences is difficult as long as only mean speed is known. To further improve knowledge about the relationship between speed and road safety, it is therefore important that studies report not just mean speed, but also characteristics of the speed distribution, in particular standard deviation.

6 CONCLUSIONS

It is concluded that in modelling the effects on road safety of changes in speed, it is important to specify the entire speed distribution and allow for risk to vary as a function of speed. Drivers belonging to the upper end of the speed distribution should be assumed to have a higher fatality and injury rate than drivers belonging to the lower end of the speed distribution. Sufficient precision in analysis is obtained by assuming that speed has a normal distribution and by defining twelve intervals of this distribution, each comprising half a standard deviation of speed. By adopting such a framework, one may, for example, account for the fact that measures having a greater effect on high speeds than on low speeds are likely to have a greater effect on fatalities and injuries than their effect on mean speed would suggest.

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LIST OF FIGURES AND TABLES

Figure 1:

Actual distribution of speed compared to normal distribution. Based on Kloeden et al. 2001

Figure 2:

Uniform speed reduction of 6 km/h

Figure 3:

Largest reduction of highest speeds

Figure 4:

Reduction of variance throughout distribution

Figure 5:

Smaller share of high speeds (enforcement)

Table 1:

Specification of speed distribution

Table 2:

Estimating effect of uniform speed reduction

Table 3:

Estimating effect of largest reduction of highest speeds

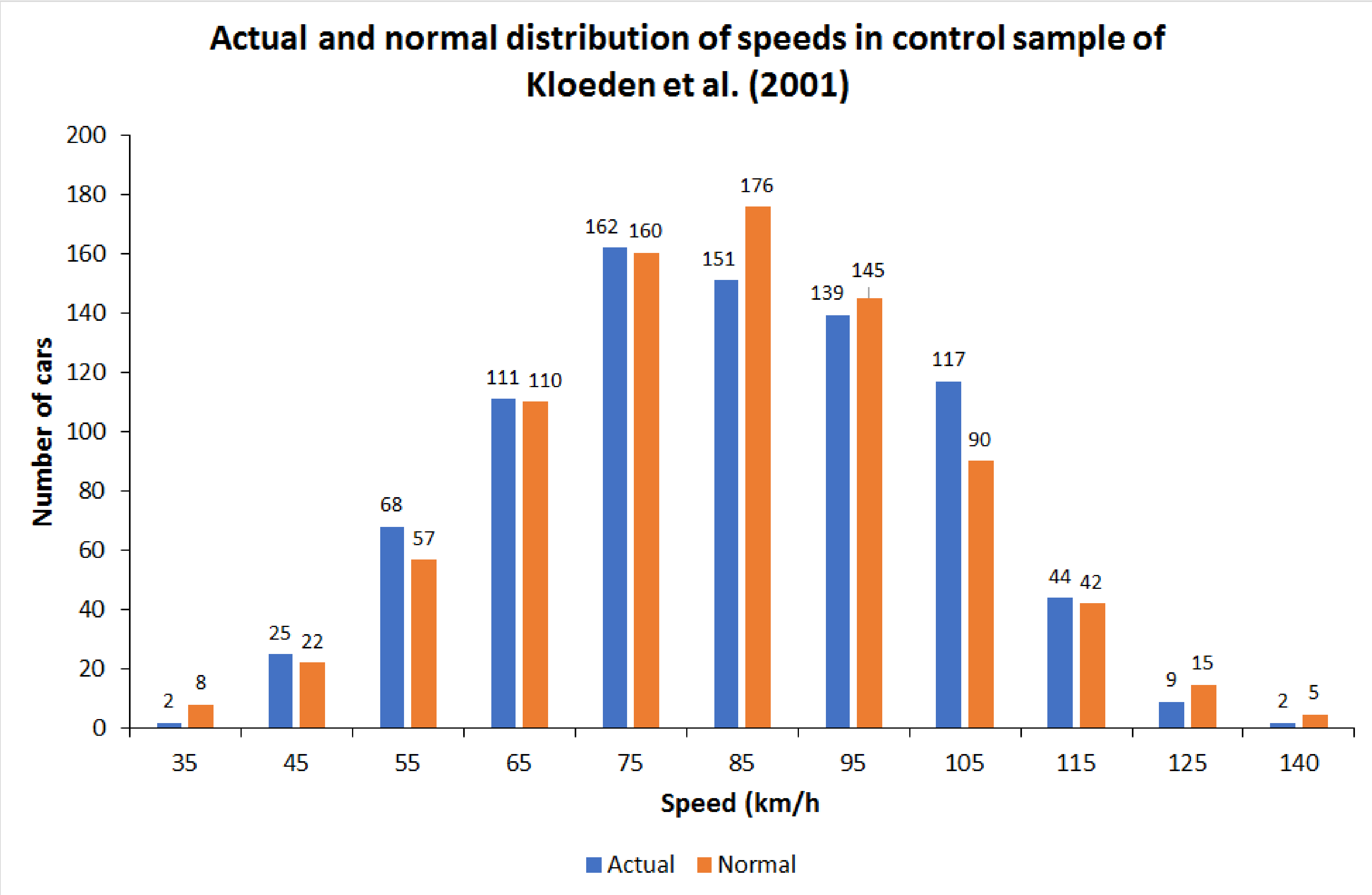
Table 4:

Estimating effect of reduced variance

Table 5:

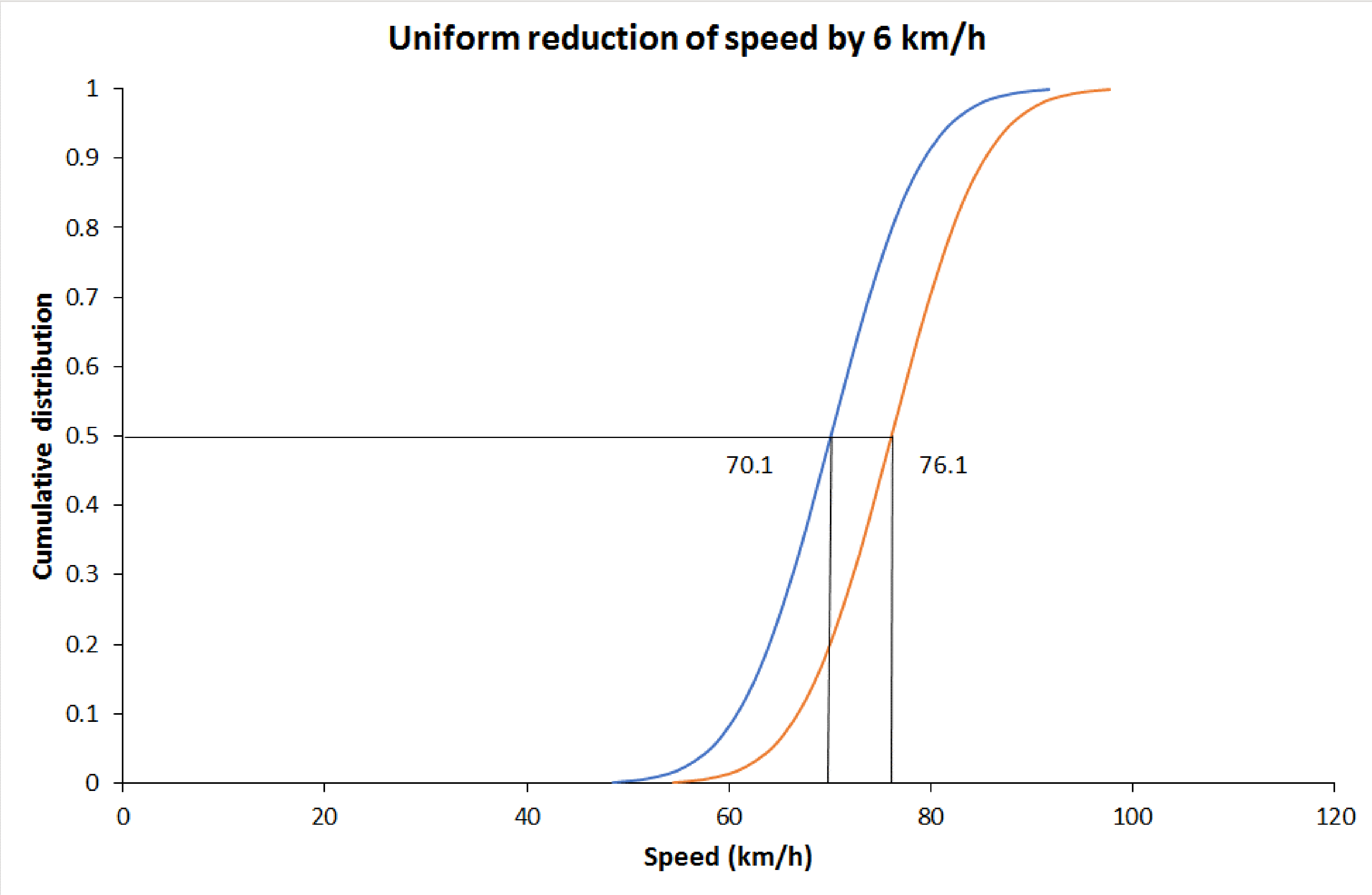
Estimating effect of smaller share of high speeds

Figure 1:



Actual and normal distribution of speeds in control sample of Kloeden et al. (2001)
Number of cars
200
180
160
140
120
100
80
60
40
20
0
2
8
25
22
68
57
111
110
162
160
151
176
139
145
117
90
44
42
9
15
2
5
35
45
55
65
75
85
95
105
115
125
140
Speed (km/h
Actual
Normal

Figure 2:



Uniform reduction of speed by 6 km/h
Cumulative distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
70.1
76.1
0
20
40
60
80
100
120
Speed (km/h)

Figure 3:

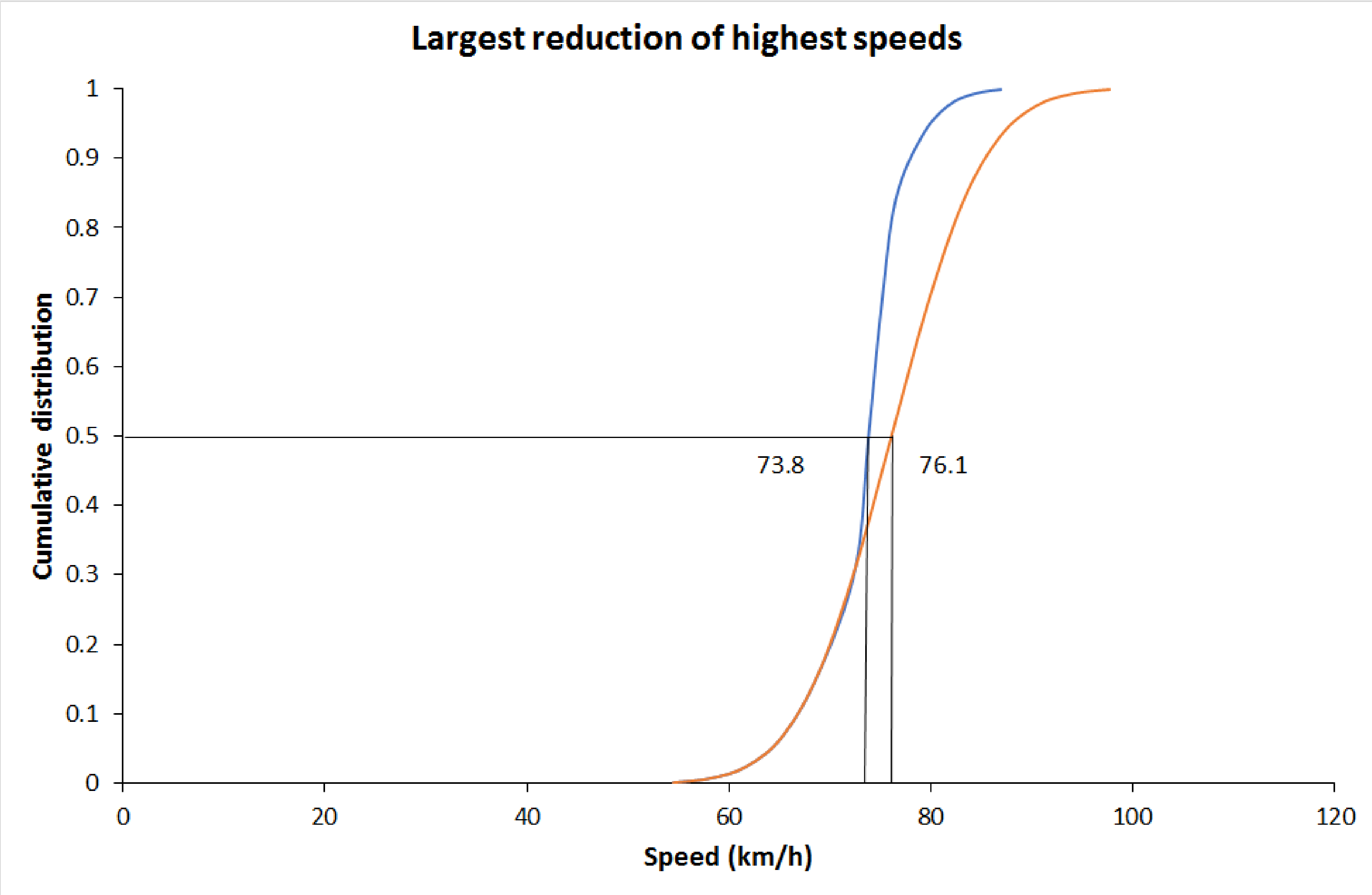
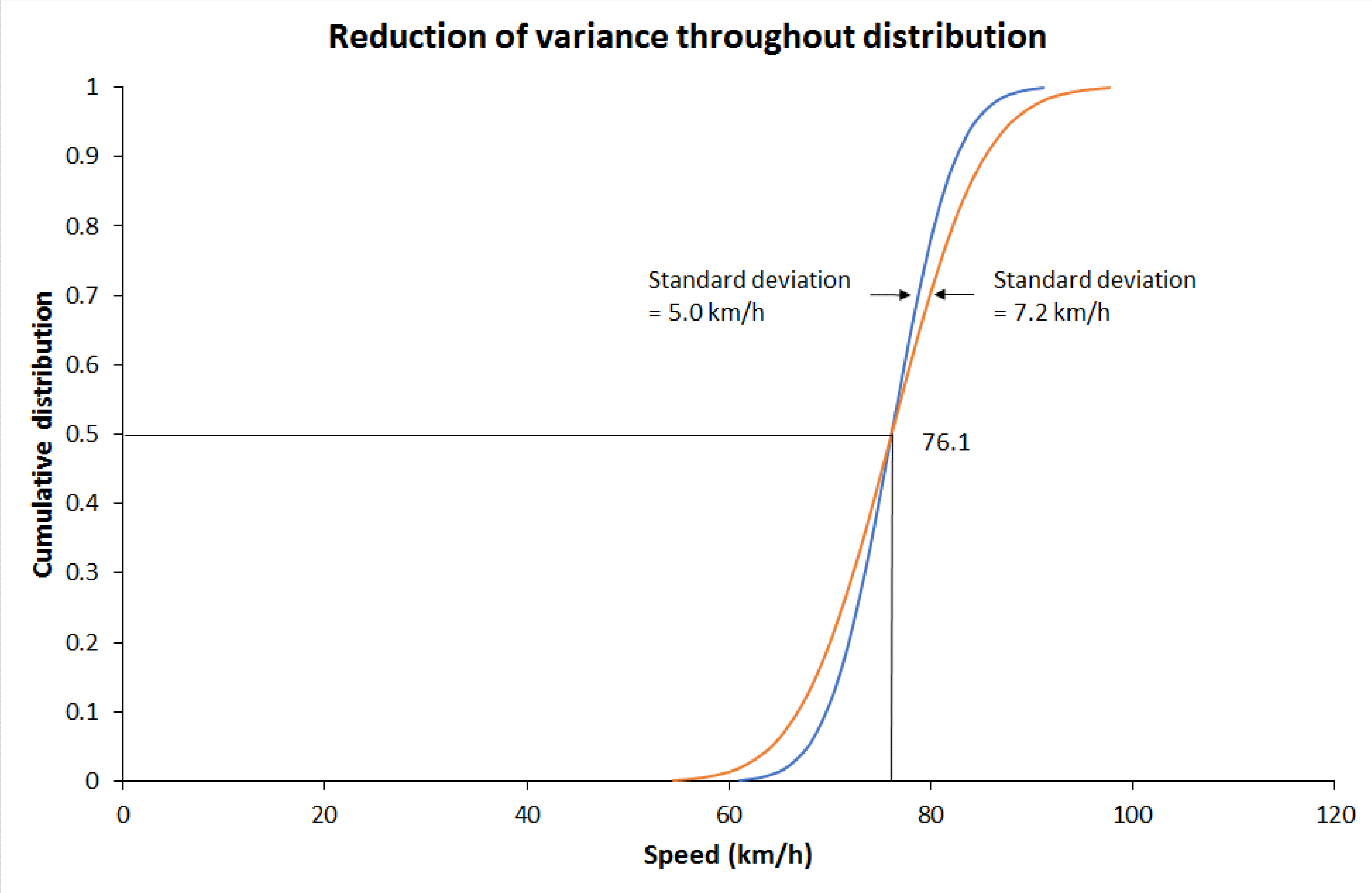

Largest reduction of highest speeds
Cumulative distribution
Speed (km/h)
73.8
76.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120

Figure 4:



Reduction of variance throughout distribution
Cumulative distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard deviation
= 5.0 km/h
Standard deviation
= 7.2 km/h
76.1
0
20
40
60
80
100
120
Speed (km/h)

Figure 5:

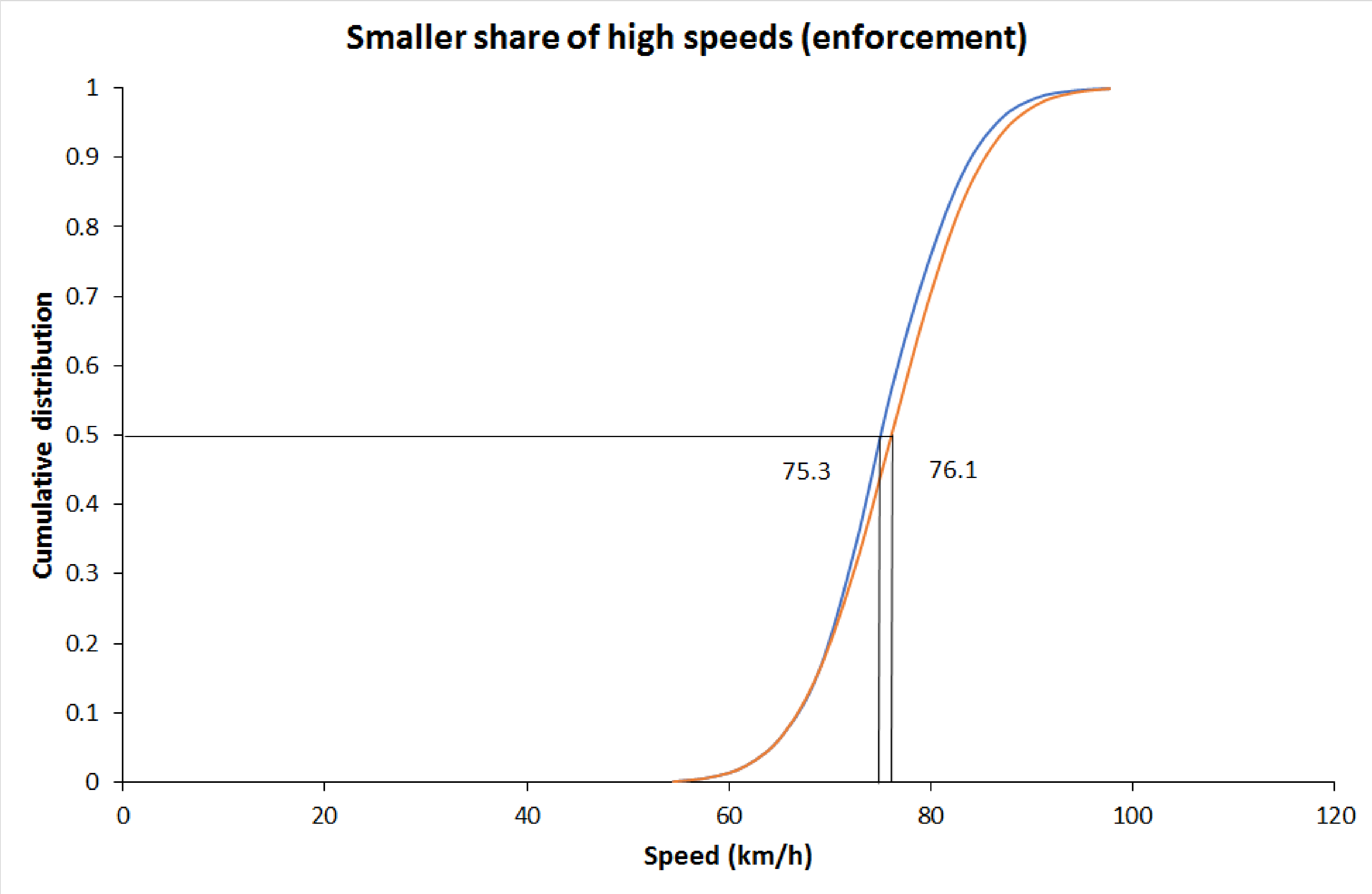

Smaller share of high speeds (enforcement)
Cumulative distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
75.3
76.1
0
20
40
60
80
100
120
Speed (km/h)

Table 1:

Interval (standard deviations)	Share of distribution (%)	Mean speed (km/h)	Relative fatality rate	Contribution to fatalities	Relative serious injury rate	Contribution to serious injuries	Relative slight injury rate	Contribution to slight injuries
2.5-3 above	0.6	95.9	4.874	2.92	3.281	1.97	2.208	1.32
2.5-2 above	1.7	92.3	3.655	6.21	2.643	4.49	1.912	3.25
2-1.5 above	4.4	88.7	2.740	12.06	2.130	9.37	1.655	7.28
1.5-1 above	9.2	85.1	2.054	18.90	1.716	15.49	1.433	13.19
1-0.5 above	15.0	81.5	1.540	23.11	1.383	20.74	1.241	18.62
0.5-0 above	19.1	77.9	1.155	22.06	1.114	21.28	1.075	20.53
0-0.5 below	19.1	74.3	0.866	16.54	0.898	17.14	0.931	17.77
0.5-1 below	15.0	70.7	0.649	9.74	0.723	10.85	0.806	12.09
1-1.5 below	9.2	67.1	0.487	4.48	0.583	5.36	0.698	6.42
1.5-2 below	4.4	63.5	0.365	1.61	0.470	2.07	0.604	2.66
2-2.5 below	1.7	59.9	0.274	0.47	0.378	0.64	0.523	0.89
2.5-3 below	0.6	56.3	0.205	0.12	0.305	0.187	0.453	0.27
Total or mean	100.0	76.1	1.000	118.21	1.000	109.88	1.000	104.28

Table 2:

Interval (standard deviations)	Share of distribution (%)	Initial mean speed (km/h)	New mean speed (km/h)	Initial relative fatality rate	Initial contribution to fatalities	New relative fatality rate	New contribution to fatalities	Reduction of number of fatalities
2.5-3 above	0.6	95.9	89.9	4.874	2.92	3.016	1.81	1.11
2.5-2 above	1.7	92.3	86.3	3.655	6.21	2.261	3.84	2.37
2-1.5 above	4.4	88.7	82.7	2.740	12.06	1.696	7.46	4.60
1.5-1 above	9.2	85.1	79.1	2.054	18.90	1.271	11.70	7.20
1-0.5 above	15.0	81.5	75.5	1.540	23.11	0.953	14.30	8.81
0.5-0 above	19.1	77.9	71.9	1.155	22.06	0.715	13.65	8.41
0-0.5 below	19.1	74.3	68.3	0.866	16.54	0.536	10.23	6.31
0.5-1 below	15.0	70.7	64.7	0.649	9.74	0.402	6.03	3.71
1-1.5 below	9.2	67.1	61.1	0.487	4.48	0.301	2.77	1.71
1.5-2 below	4.4	63.5	57.5	0.365	1.61	0.226	0.99	0.62
2-2.5 below	1.7	59.9	53.9	0.274	0.47	0.169	0.29	0.18
2.5-3 below	0.6	56.3	50.3	0.205	0.12	0.127	0.08	0.04
Total or mean	100.0	76.1	70.1	1.000	118.21	0.619	73.14	45.07

Table 3:

Interval (standard deviations)	Share of distribution (%)	Initial mean speed (km/h)	New mean speed (km/h)	Initial relative fatality rate	Initial contribution to fatalities	New relative fatality rate	New contribution to fatalities	Reduction of number of fatalities
2.5-3 above	0.6	95.9	85.6	4.874	2.92	2.138	1.29	1.63
2.5-2 above	1.7	92.3	83.0	3.655	6.21	1.737	2.95	3.26
2-1.5 above	4.4	88.7	80.4	2.740	12.06	1.411	6.21	5.85
1.5-1 above	9.2	85.1	77.8	2.054	18.90	1.146	10.54	8.36
1-0.5 above	15.0	81.5	75.8	1.540	23.11	0.976	14.64	8.47
0.5-0 above	19.1	77.9	74.5	1.155	22.06	0.876	16.74	5.32
0-0.5 below	19.1	74.3	73.2	0.866	16.54	0.790	15.08	1.46
0.5-1 below	15.0	70.7	70.7	0.649	9.74	0.402	9.74	0.00
1-1.5 below	9.2	67.1	67.1	0.487	4.48	0.301	4.48	0.00
1.5-2 below	4.4	63.5	63.5	0.365	1.61	0.226	1.61	0.00
2-2.5 below	1.7	59.9	59.9	0.274	0.47	0.169	0.47	0.00
2.5-3 below	0.6	56.3	56.3	0.205	0.12	0.127	0.12	0.00
Total or mean	100.0	76.1	73.8	1.000	118.21	0.709	83.86	34.35

Table 4:

Interval (standard deviations)	Share of distribution (%)	Initial mean speed (km/h)	New mean speed (km/h)	Initial relative fatality rate	Initial contribution to fatalities	New relative fatality rate	New contribution to fatalities	Reduction of number of fatalities
2.5-3 above	0.6	95.9	89.9	4.874	2.92	3.004	1.80	1.12
2.5-2 above	1.7	92.3	87.4	3.655	6.21	2.460	4.18	2.43
2-1.5 above	4.4	88.7	84.9	2.740	12.06	2.014	8.86	3.20
1.5-1 above	9.2	85.1	82.4	2.054	18.90	1.649	15.17	3.73
1-0.5 above	15.0	81.5	79.9	1.540	23.11	1.350	20.25	2.86
0.5-0 above	19.1	77.9	77.4	1.155	22.06	1.105	21.11	0.95
0-0.5 below	19.1	74.3	74.9	0.866	16.54	0.905	17.28	-0.74
0.5-1 below	15.0	70.7	72.4	0.649	9.74	0.741	11.11	-1.37
1-1.5 below	9.2	67.1	69.9	0.487	4.48	0.607	5.58	-1.10
1.5-2 below	4.4	63.5	67.4	0.365	1.61	0.497	2.18	-0.57
2-2.5 below	1.7	59.9	64.9	0.274	0.47	0.407	0.69	-0.22
2.5-3 below	0.6	56.3	62.4	0.205	0.12	0.333	0.20	-0.08
Total or mean	100.0	76.1	76.1	1.000	118.21	0.917	108.42	9.79

Table 5:

Interval (standard deviations)	Initial share of distribution (%)	New share of distribution (%)	Initial mean speed (km/h)	New mean speed (km/h)	Initial relative fatality rate	Initial contribution to fatalities	New contribution to fatalities	Reduction of number of fatalities
2.5-3 above	0.6	0.3	95.9	95.9	4.874	2.92	1.46	1.46
2.5-2 above	1.7	1.0	92.3	92.3	3.655	6.21	3.65	2.56
2-1.5 above	4.4	3.1	88.7	88.7	2.740	12.06	8.49	3.57
1.5-1 above	9.2	7.4	85.1	85.1	2.054	18.90	15.20	3.70
1-0.5 above	15.0	13.5	81.5	81.5	1.540	23.11	20.79	2.32
0.5-0 above	19.1	18.1	77.9	77.9	1.155	22.06	20.90	1.16
0-0.5 below	19.1	22.7	74.3	74.3	0.866	16.54	19.74	-3.20
0.5-1 below	15.0	17.9	70.7	70.7	0.649	9.74	11.62	-1.88
1-1.5 below	9.2	9.2	67.1	67.1	0.487	4.48	4.48	0.00
1.5-2 below	4.4	4.4	63.5	63.5	0.365	1.61	1.61	0.00
2-2.5 below	1.7	1.7	59.9	59.9	0.274	0.47	0.47	0.00
2.5-3 below	0.6	0.6	56.3	56.3	0.205	0.12	0.12	0.00
Total or mean	100.0	100.0	76.1	75.3	1.000	118.21	108.55	9.66