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Speed enforcement in Norway: testing a game-theoretic model of the interaction between drivers and the police

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ABSTRACT

This paper probes the relationship between changes in the risk of apprehension for speeding in Norway and changes in the amount of speeding. The paper is based on a game-theoretic model of how the rate of violations and the amount of enforcement is determined by the interaction between drivers and the police. This model makes predictions both about how drivers will adapt to changes in the amount of enforcement (the more enforcement, the less violations) as well as how the police will adapt to changes in the rate of violations (the less violations, the less enforcement). The paper attempts to test the game-theoretic model empirically. Testing the model rigorously is difficult, mainly because some of the relevant variables are not reliably measured and are endogenous. Two models were developed: one to identify sources of changes in the rate of violations, one to identify sources of changes in the amount of enforcement. The predictions of the game-theoretic model were supported, although the results were not statistically significant in the model of how the police adapt enforcement to changes in the rate of violations.

Key words: speed enforcement; rate of violations; risk of apprehension; statistical relationship; game-theoretic model

1 INTRODUCTION

Traffic offences remain a large road safety problem. An estimate for Norway (Elvik 2011) suggests that the number of traffic fatalities can be reduced by more than 50 percent and the number of traffic injuries reduced by more than 30 percent by eliminating 15 different traffic violations. Eliminating traffic offences is not a realistic objective in the short run. There are limits to how much police enforcement there can be. The police cannot be everywhere at all times. Technology such as speed cameras is used to enforce traffic law. However, this technology is expensive and cannot be deployed everywhere at all times. Vehicle technology, like speed monitoring and recording systems, can in principle replace current means of enforcement, but is still not widely used.

One potential limit to conventional police enforcement that has not been studied extensively, is how the police adapt enforcement to changes in the rate of violations. If the rate of a certain violation is very low, as is the case in Norway for drinking-and-driving (which makes up less than 0.5 percent of all driving), the police may find it unproductive to do enforcement specifically targeted at the violation, because they would need to check hundreds or maybe thousands of sober drivers before encountering a drunk driver. A game-theoretic model of police enforcement proposed by Bjørnskau and Elvik (1992) suggests that the police reduce enforcement in response to a decline in violations and increase it in response to an increase in violations. If this is the case, enforcement will in the long run never become sufficient to deter all violations. Once violations drop to a low level, the police will reduce enforcement, which in turn will lead to more violations. This pattern may repeat itself many times, as there is no stable equilibrium in the game.

The objective of this paper is to test the game-theoretic model of police enforcement empirically. This is done by means of data on speeding and speed enforcement in Norway for the years 2004-2013. The game-theoretic model will first be presented. Then, data relevant for testing the model will be discussed.

2 A GAME-THEORETIC MODEL OF SPEED ENFORCEMENT

The logic of the game-theoretic model of speed enforcement is perhaps best understood by explaining it by reference to a numerical example, taken from Bjørnskau and Elvik (1992) and reproduced in Table 1.

Table 1 about here

Table 1 shows the game in normal form. The entries are the payoffs to drivers and the police associated with the various choices. The payoff to the police is indicated in the upper right corner of each cell of the Table. The payoff to drivers is indicated in the lower left corner of each cell of the Table. Starting in the upper left cell, it can be seen that drivers can improve their payoff (from –300 to –50) by complying with the speed limit. This will result in a move to the lower left cell of the Table. However, once drivers comply with speed limits, it is seen that the police can improve their payoff (from –10000 to 0) by not enforcing. This results in a move to the lower right cell of the Table. From that cell, it is seen that drivers can improve their payoff (from –50 to 50) by speeding. This results in a move to the upper right cell of the Table. However, when drivers are speeding, the police can improve their payoff (from –20000 to –10000) by enforcing. This brings the game back to the upper left cell where it started and the circle can go on forever. The game, in other words, has no solution in pure strategies.

It does have a solution in mixed strategies. A mixed strategy is to choose between the pure strategies with certain probabilities. Thus, with the payoffs used as example in Table 1, the police should enforce with a probability of 0.2857 and not enforce with a probability of 0.7143. Drivers should speed with a probability of 0.50 and not speed with a probability of 0.50. See the paper by Bjørnskau and Elvik (1992) for details regarding how the mixed-strategy solution was obtained.

What are the main implications of the game-theoretic model? The following implications are relevant for empirical testing of the model:

1. When enforcement increases, the rate of violations will be reduced.
2. When enforcement decreases, the rate of violations will increase.
3. When the rate of violations increases, enforcement will increase.
4. When the rate of violations decreases, enforcement will decrease.
5. Making sanctions more severe will have no effect on the rate of violations.
6. Making sanctions more severe will lead to less enforcement.

3 DATA ON SPEEDING AND ENFORCEMENT

To test the game-theoretic model, data are needed about the rate of violations, the amount of enforcement and changes in these variables over time. The rate of violations is the number of offences committed divided by vehicle kilometres of travel. For most traffic offences, the rate of violations is unknown, since most violations go undetected. A few violations are, however, recorded in a sufficiently systematic manner to permit an estimation of their rate of occurrence. The focus of this study is speeding, the rate of which is defined as (Elvik and Amundsen 2014):

$$\text{Rate of speeding} = \frac{Kilometres\ driven\ while\ speeding}{Total\ kilometres\ of\ travel}$$

The data used to estimate the rate of speeding were provided by the Public Roads Administration on an Excel spreadsheet. For each of the speed limits 50, 60, 70, 80, 90 and 100 km/h the data showed mean speed, 85 percentile speed and percentage of vehicles above the speed limit. Annual data for the years from 2004 to 2013 were provided. Three ranges of speeding were defined for the analyses reported in this paper:

1. Speeding between 6 and 10.9 kilometres per hour above the speed limit
2. Speeding between 11 and 15.9 kilometres per hour above the speed limit.
3. Speeding 16 kilometres per hour or more above the speed limit.

Small violations, less than 6 kilometres per hour above the speed limit, are tolerated. The effective risk of apprehension for speeding by less than 6 kilometres per hour is zero.

The other key concept of the study is the amount of enforcement. Unfortunately, there is only crude summary information available about this, in the form of the total number of drivers stopped by the police each year. This number cannot be broken down according to the reason for stopping drivers, such as speeding, running red lights, etc. As a proxy for enforcement, the citation rate for speeding has therefore been used. Citation rate is measured as the number of citations per million kilometres driven while committing a violation:

$$\text{Citation rate} = \frac{Number\ of\ citations}{Kilometres\ driven\ while\ speeding}$$

Citation rate may not be strictly proportional to the amount of enforcement. Thus, as an example, if enforcement is increased by a factor of four one might expect the number of citations to increase by a factor of, for example, three if the increase in enforcement deters some violations. In Norway, however, the citation rate for speeding is extremely low, on the average only a little more than 10 citations per million vehicle kilometres driven while speeding (Elvik and Amundsen 2014). Even if the citation rate was doubled, the probability that a speeding driver would be cited would remain very low. The citation rate for speeding in Norway is therefore probably nearly proportional to the amount of enforcement. Police statistics support this assumption. Between 2004 and 2013 the number of citations for speeding remained close to 12 percent of the total number of drivers stopped by the police, with no clear trend over time.

There are three types of citations (sanctions) for speeding in Norway:

1. Fixed penalties. These are traffic tickets with standardised amounts to be paid, issued on the spot. If the road user pleads guilty, the case is closed. They are used for speeding up to about 35 kilometres per hour above the speed limit.

2. Fines. These are traffic tickets determined on a case-by-case basis with regard to the income of the road user. They are used for speeding by more than 35 kilometres per hour above the speed limit.
3. Formal charges. For serious traffic offences, the police will file formal charges and the case will go to court. This is used for speeding by more than about 50 kilometres per hour above the speed limit.

Statistics on the number of citations issued each year are kept both by the police and by the Norwegian National Collection Agency. These statistics are quite detailed and were obtained on Excel spreadsheets. Years from 2004 to 2013 were used (Elvik and Amundsen 2014).

Estimates of the total number of vehicle kilometres of travel, kilometres driven while speeding and the number of citations for speeding are given in Table 2 for each year from 2004 to 2013. A distinction is made between speed limits up to 60 kilometres per hour and speed limits from 70 kilometres per hour and above. The reason for defining these two groups is that the fixed penalties for speeding are different in the two groups.

Table 2 about here

For speed limits up to 60 kilometres per hour, the number of citations has increased for violations between 6 and 10.9 kilometres per hour, but stayed more or less stable for speeding in the ranges of 11 to 15.9 kilometres per hour and 16 or more kilometres per hour. Despite the overall stability, there are annual changes in both directions in the number of citations.

For speed limits of 70 kilometres per hour or higher, the number of citations first increased, then declined for speeding in the range of 6 to 10.9 kilometres per hour. For the other ranges of speeding, there is a tendency for the number of citations to go down.

4 MODEL DEVELOPMENT

In order to test the game-theoretic model empirically, a suitable model of the relationship between changes in the amount of enforcement and changes in the rate of speeding must be developed. There are three main analytic choices to be made:

1. How best to represent changes in the rate of speeding and the amount of enforcement.
2. How to deal with the endogeneity of the key variables in the study.
3. How to identify and control for potentially confounding factors influencing both speeding and enforcement.

An exploratory analysis found that annual changes in speeding and enforcement were best represented as ratios, i.e. as the rate in year T + 1 divided by the rate in year T. Definitions of the rate of speeding and the citation rate (used to indicate enforcement) were given in section 3 above. Thus, if the rate of speeding was, say, 0.097 in year T and 0.094 in year T + 1, the ratio is 0.094/0.097 = 0.964. Similar ratios showing annual changes were defined for enforcement. Figure 1 shows a scatter plot of the relationship between changes in enforcement (citation rate) and changes in the rate of speeding.

Figure 1 about here

It is seen that there is a tendency for the rate of speeding to be reduced when citation rate increases. When citation rate is reduced, there is a tendency for the rate of speeding to increase. The data points are, however, widely scattered around the trend line fitted in the Figure. A power function fitted the data in Figure 1 best, but it explained only 25 percent of the variance.

Both variables of principal interest in this study are endogenous, i.e. both variables are influenced by the other variable and are thus not fully independent. There are several options for dealing with this problem. In this paper, the assumption is made that the effects of enforcement on violation rate are instantaneous. Once there is enforcement, drivers react to it immediately. Once enforcement ceases, drivers revert to their prior behaviour almost immediately; any so-called "time-halo" effect is short. These assumptions are supported by a literature survey (Vaa 1993). Thus, when one year is smallest unit of time, changes in the amount of enforcement in year T will have an effect on speeding the same year.

Police adaptation to changes in violation rate is assumed to be delayed by one year. While no study has been found that verifies this assumption, it is nevertheless reasonable. It is only at the end of each year, when statistics are compiled, that the police can reliably determine whether there has been a change in violation rates. Moreover, budgets are made on an annual basis and changes in priorities made only from one year to the next, not by improvising during each year. It is therefore assumed that changes in violation rates in year T are associated with changes in police activity in year T + 1. Two separate models have therefore been developed:

one for driver adaptation to enforcement, and one for police adaptation to driver behaviour.

The third analytic choice to be made concerns what potentially confounding variables to include in the analysis. During the period covered by this study, there was a trend for both the mean speed of traffic and the rate of speeding to go down in Norway (Høye, Bjørnskau and Elvik 2014). To control for this trend, year was included as a variable in the form of a count (from 1 to 9). Fixed penalties for speeding increased in 2005, but remained unchanged in all later years. Changes in the real value of fixed penalties were measured using real wages as a deflator. Real wages were preferred as a deflator to the consumer price index, as there was a substantial increase in real wages in Norway during the period covered by this study, making the fixed penalties considerably cheaper in real terms (except in the single year 2005).

Wolff (2014) found that speeding is reduced when fuel price increases. The real price of fuel was therefore included in the analysis, again using real wages as deflator. All variables included in the analysis are listed in Table 3. The variables are defined as follows:

1. Year (entered as a count 1, 2, …, 9)
2. Rural dummy (urban = 0; rural = 1; speed limits and fixed penalties are higher in rural areas)
3. Violation level (1 = 6-10 km/h; 2 = 11-15 km/h; 3 = 16- km/h)
4. Ln(Δcitations) (the natural logarithm of annual change (Δ) in citation rate, given as the ratio: (citation rate in year T + 1)/(citation rate in year T); citation rate = citations/million km driven while speeding)

5. Ln(Δpenalties) (the natural logarithm of annual change (Δ) in fixed penalties, deflated by real wages)
6. Ln(Δfuel price) (the natural logarithm of annual change (Δ) in the price of fuel, deflated by real wages)
7. Ln(Δenforcement) (the natural logarithm of annual change (Δ) in the number of drivers checked by the police)
8. Ln(Δviolations) (the natural logarithm of annual change (Δ) in the rate of speeding, given as the ratio (speeding rate in year T+ 1)/(speeding rate in year T); speeding rate = km driven while speeding/all km driven
9. Ln(Δlagged citations) (the natural logarithm of annual change (Δ) in the number of citations, lagged by one year)

Table 3 about here

Table 3 shows the correlations between the variables. In general, the correlations are moderate and should not generate any co-linearity problems. Variables 1 to 7 were used as independent variables in the analysis of how drivers adapt to changes in enforcement. Variable 8 was the dependent variable. Variables 1-3, 5 and 8 were used as independent variables in the analysis of police adaptation to changes in violation rate. Variable 9 was the dependent variable. Ordinary least squares regression was applied.

All variables describing annual changes were converted to natural logarithms. An advantage of this conversion is that in cases of no change in the independent variables (i.e. the variables take on the value of 1), there will be no change in the dependent variable, since the natural logarithm of 1 equals zero. Furthermore, the coefficients can be interpreted as elasticities, i.e. they indicate the percentage change in the dependent variable associated with a 1 percent increase in the independent variable. There were 54 data points in the analysis of driver adaptation to changes in speed enforcement (9 years · 2 values for traffic environment (rural/urban) · 3 violation levels). There were 48 data points in the analysis of police adaptation to changes in the rate of speeding (8 years; one year lost due to lagging · 2 values for traffic environment (rural/urban) · 3 violation levels).

5 RESULTS

The results of analysis are presented in Table 4. The upper panel of the table presents results for driver adaptation to changes in enforcement. The lower panel of the table presents results for police adaptation to changes in the rate of speeding.

Table 4 about here

All coefficients in the model of driver adaptation are negative, except for the constant term. Changes in citation rate has the largest effect. The effect is consistent with the predictions of the game-theoretic model. When citation rate is reduced, violation rate increases. When citation rate increases, violation rate decreases. Based on the coefficient, it can be estimated that a 25 percent reduction of citation rate will be associated a 10.6 percent increase in violation rate. A 50 percent increase in citation rate will be associated with a 13.2 percent reduction in violation rate.

The game-theoretic model predicts that increasing penalties will have no effect on violation rate. A previous study (Elvik and Christensen 2007) did not find that speeding was reduced when penalties were increased. Table 4 shows a negative coefficient for penalties, indicating that increased penalties are associated with less speeding. The coefficient is, however far from statistically significant and the effect is small. Based on the coefficient, it can be estimated that an 80 percent increase of fixed penalties will be associated with a 5 percent reduction in speeding.

Turning to the results for the police, the model fitted the data poorly and explained only a little more than 10 percent of the variance. None of the regression coefficients were statistically significant at conventional levels. The signs of the coefficients were consistent with the predictions of the game-theoretic model, but the standard errors show that the coefficients cannot really be distinguished from zero. A larger data set is needed to estimate the coefficients more precisely.

Figure 2 is an attempt to illustrate the main findings. It presents an Edgeworth box showing how drivers and the police adapt to changes in violations and enforcement. The lower part of the box shows how drivers adapt to changes in enforcement, as shown by the downward sloping curve. The upper part of the box, which must be read "upside-down" shows how the police adapt to violation rate. The curve shows that an increase in violation rate is associated with an increase in enforcement. The curve is considerably flatter than the curve for drivers, consistent with the finding that, although the police may adapt, any adaptation is smaller than the adaptation of drivers to changes in enforcement.

Figure 2 about here

6 DISCUSSION AND CONCLUSIONS

It has been argued that road safety evaluation research needs to develop a firmer theoretical foundation (Davis et al. 2008). The lack of a more developed theoretical foundation for this research means that few results can be ruled out on theoretical grounds. Thus, while it is entirely reasonable to expect road lighting to reduce the number of accidents, the opposite cannot be ruled out. If lighting is of poor quality; if drivers nevertheless adapt to it by increasing speed; if vehicles strike lighting poles more often than normal, an increase in the number of accidents may occur for entirely plausible reasons.

Game theory is unique by predicting road user behavioural adaptation to safety measures. The game theoretic model presented in this paper not only predicts road user adaptation to enforcement; it also predicts how the police will react to changes in driver behaviour, in particular the rate of violations. These mutual behavioural adaptations may explain why speeding is a persistent problem in most motorised countries. In the first place, minor violations are in practice tolerated; a safety margin is always applied before the police cite a driver for speeding. In the second place, once speeding has been reduced to an "acceptable" level, police will reduce enforcement. The acceptable level is likely to be a rate of speeding considerably above zero. Such a mechanism is perhaps particularly likely to operate if there is a downward trend in the number of traffic fatalities, as has been the case in Norway in recent years. Why bother about speeding if the number of fatalities is going down anyway?

In the long run, vehicle technology may replace speed enforcement. For the time being, however, this technology is not widely used. Enforcement performed by police officers is therefore still a key road safety measure in order to deter speeding and other traffic violations. The key findings of the research presented in this paper can be summarised as follows:

1. Drivers adapt to changes in the amount of speed enforcement by speeding less when enforcement increases and speeding more when enforcement is reduced.
2. Increasing the fixed penalties for speeding is associated with a weak, not statistically significant, reduction of speeding.
3. Results suggests that the police adapt the amount of enforcement to changes in the rate of speeding, although the results are not statistically significant.
4. There is no conclusive evidence showing that increasing the fixed penalties for speeding influences enforcement, but the sign of the coefficient is consistent with the game-theoretic model.

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LIST OF FIGURES AND TABLES

Table 1:

		The police	
		Enforce	Not enforce
Drivers	Violate speed limit	–300 ; –10000	50 ; –20000
	Not violate speed limit	–50 ; –10000	–50 ; 0

Table 2:

	Million vehicle km of travel – total and by range for speeding				Annual number of citations for speeding		
Year	Total	Speeding 6-10.9 km/h	Speeding 11-15.9 km/h	Speeding 16 or more km/h	Citations for speeding 6-10.9	Citations for speeding 11-15.9	Citations for speeding 16-
				Part A: Speeds limit up to 60 kilometres per hour			
2004	12697	1236	367	70	30061	36750	19258
2005	12987	1219	358	67	35789	35931	18364
2006	13127	1223	359	65	38928	35018	18194
2007	13451	1284	398	81	43476	36185	19238
2008	13541	1235	376	75	42979	33059	17523
2009	13528	1268	397	87	37774	30283	16067
2010	13549	1165	344	66	35330	32859	18334
2011	13661	1050	291	49	38630	33476	17148
2012	13799	1035	308	60	40971	36608	18733
2013	13920	1026	306	58	42034	37510	18532
				Part B: Speed limits of 70 kilometres per hour or more			
2004	26012	2025	813	254	16753	41425	51329
2005	26729	2050	819	255	25250	39755	45211
2006	27304	2244	912	292	39429	46916	48482
2007	28234	2184	871	277	44183	41531	45676
2008	28686	2230	911	309	41864	38342	42938
2009	28923	2161	862	285	38134	30737	38142
2010	29327	2169	867	294	41933	33356	39849
2011	29844	2131	822	269	33896	26900	35574
2012	30340	2125	853	306	31472	24152	35490
2013	30795	2076	833	305	28329	22340	31248

Table 3:

	Pearson correlation coefficients							
	Rural dummy	**Violation level**	**Ln(Δcitations)**	**Ln(Δpenalties)**	**Ln(Δfuelprice)**	**Ln(Δenforcement)**	**Ln(Δviolations)**	**Ln(Δlaggedcita)**
Year	0.000	0.000	-0.136	-0.392	-0.194	-0.293	-0.133	-0.063
Rural dummy		0.000	-0.219	-0.175	0.000	0.000	0.113	-0.264
Violation level			-0.244	-0.008	0.000	0.000	0.037	-0.153
Ln(Δcitations)				0.079	0.424	0.328	-0.503	0.288
Ln(Δpenalties)					0.237	0.296	-0.062	0.065
Ln(Δfuel price)						0.272	-0.241	-0.226
Ln(Δenforcement)							-0.151	0.427
Ln(Δviolations)								0.066

Violation level is an indicator of the level of speeding: 1 = 6-10 km/h; 2 = 11-15 km/h; 3 = 16 or more km/h above the speed limit

Ln denotes the natural logarithm

Δ is change from one year to the next, stated as a ratio, e.g.: (violation rate in year T + 1)/(violation rate in year T)

Table 4:

Variable	Coefficient	Standard error	P-value	Standardised coefficients (betas)
	Panel A: Model of driver adaptation to changes in speed enforcement. Dependent variable: Ln(Δspeeding rate)			
Constant term	0.053	0.043	0.228	
Year count	-0.009	0.005	0.061	-0.261
Rural dummy	-0.005	0.024	0.838	-0.027
Violation level	-0.011	0.014	0.452	-0.097
Ln(Δcitation rate)	-0.349	0.097	0.001	-0.543
Ln(Δpenalties)	-0.088	0.106	0.411	-0.117
Ln(Δfuel price)	-0.061	0.269	0.822	-0.032
Ln(Δenforcement)	-0.008	0.184	0.965	-0.006
Squared multiple correlation (R^2)	0.317			
Mean autocorrelation of residuals for lags 1 through 16	-0.023			
	Panel B: Model of police adaptation to changes in violation rate (speeding). Dependent variable: Ln(Δcitation rate lagged)			
Constant term	0.100	0.073	0.181	
Year count	-0.003	0.010	0.761	-0.050
Rural dummy	-0.076	0.041	0.072	-0.277
Violation level	-0.026	0.024	0.287	-0.157
Ln(Δpenalties)	-0.002	0.175	0.990	-0.002
Ln(Δviolation rate)	0.139	0.209	0.509	0.100
Squared multiple correlation (R^2)	0.107			
Mean autocorrelation of residuals for lags 1 through 16	-0.038			

Figure 1:

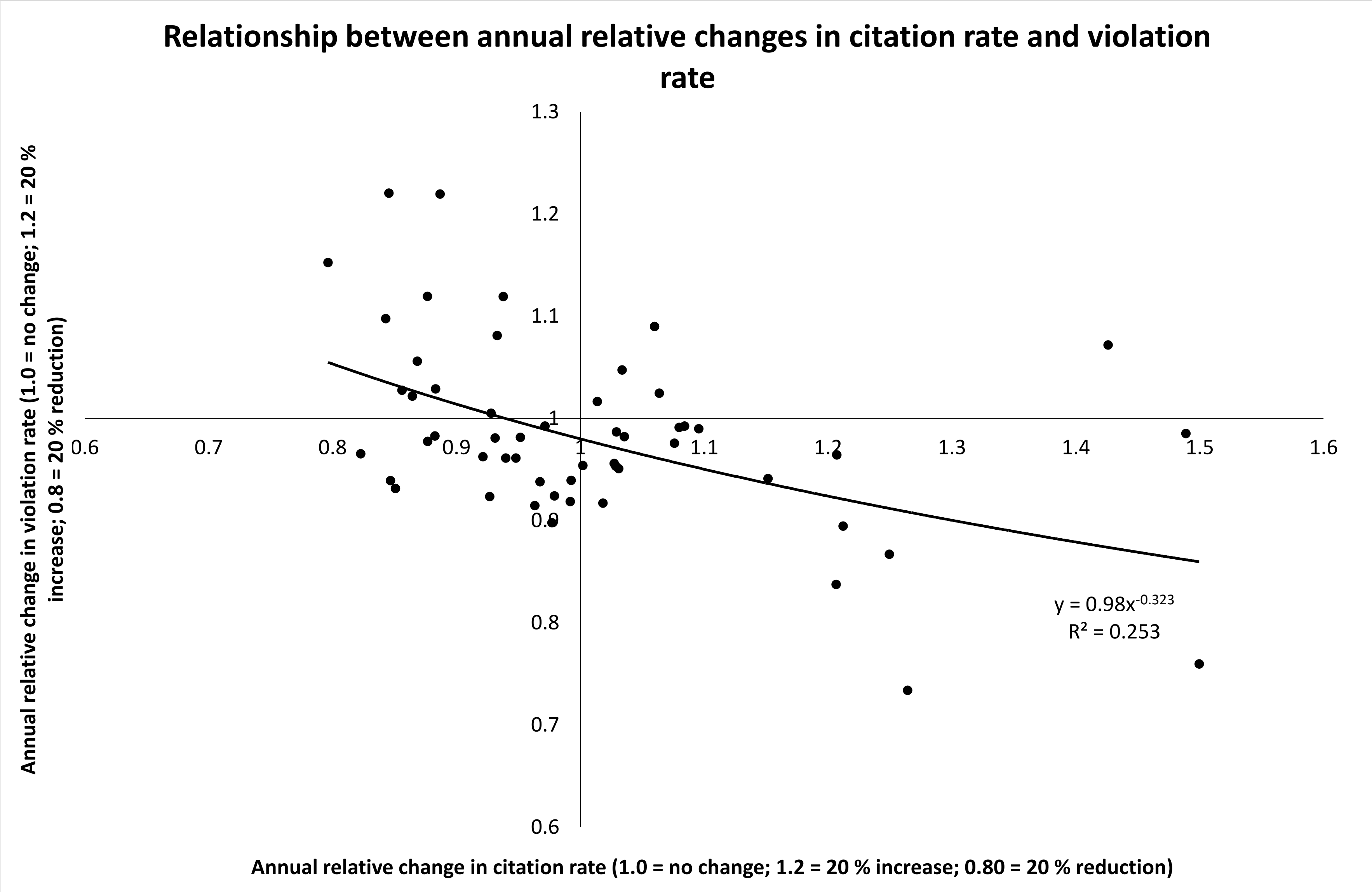
Relationship between annual relative changes in citation rate and violation rate
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
y = 0.98x-0.323
R² = 0.253
Annual relative change in violation rate (1.0 = no change; 1.2 = 20 % increase; 0.8 = 20 % reduction)
Annual relative change in citation rate (1.0 = no change; 1.2 = 20 % increase; 0.80 = 20 % reduction)

Figure 2:


Violation rate
The police adapt to increased speeding by more enforcement
Violation rate
Amount of enforcement
Drivers adapt to increased enforcement by not speeding
Amount of enforcement