THE IMPACT OF SPEED CAMERA TECHNOLOGY ON SPEED LIMIT COMPLIANCE IN MULTI-LANE TUNNELS

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ABSTRACT
This research aimed to test the impact of fixed-position speed camera technology on speed limit compliance in multi-lane tunnels. Driver speeding behaviour was examined both before and after fixed speed cameras were installed and enforcement was implemented in a multi-lane tunnel in Melbourne. Vehicle speed data were collected over two separate time periods, the first period representing speed and compliance behaviour before the introduction of cameras, and the second period representing behaviour after camera introduction and issuance of speed camera traffic infringement notices. In addition to collecting speed data at camera locations, both before and after camera operations had become prominent in the minds of drivers, corresponding speed measurements were collected at a suitable control location. The effectiveness of the fixed speed cameras was examined in terms of changes in average vehicle speeds and changes in the proportion of drivers not complying with the speed limit after implementation of speed camera enforcement. The effects of the speed camera enforcement in the tunnel were further examined according to the lane position of vehicle; the day of week of vehicle travel, and the times of day of vehicle travel.

INTRODUCTION
During the late 1990s, a major road infrastructure project, known as CityLink, was undertaken in Melbourne, Australia. This road project linked several key freeways and bridges in Melbourne's metropolitan area, via two, one-way tunnels of 1.6 kilometres (the Domain tunnel) and 3.5 kilometres (the Burnley tunnel) in length. With the opening of the CityLink tunnels, the Victoria Police were faced with a new and unique enforcement challenge. That challenge concerns the need to enforce vehicle speeds to safe and legal levels, in an environment where conventional techniques, involving Police presence, are likely to be unsafe or otherwise impractical. A multi-lane tunnel environment, with limited roadside space and high traffic volumes and speeds, requires use of efficient and effective automated enforcement methods. For these and other reasons, Victoria Police decided to evaluate the effectiveness of fixed-position speed cameras, operating on a full-time basis. However, their effect on the speed behaviour and compliance of drivers and riders was not known for this type of environment.

OBJECTIVES
The main objective was to test the impact of fixed-position speed camera technology on speed limit compliance in the CityLink tunnels. These objectives were entirely consistent with Victoria's Road Safety Strategy for 1995 - 2000, which strongly encouraged developing and using improved technology to detect speeding drivers. In order to meet the project objectives, data on driver speeding behaviour were examined both before and after the speed cameras were installed and enforcement was implemented in the CityLink Domain Tunnel.

STUDY DESIGN
This section describes the main elements of the study design, addressing issues related to:
i. the definition of before and after periods;
ii. the measures of effectiveness to be used to assess the impact of the cameras on speeding behaviour;
iii. analysis issues related to the variable speed limits applying within the tunnels;
iv. key considerations in the use and requirements of data for a control site.

Greater detail of the study design can be found in Corben, Gelb and Diamantopoulou (2000).

Definition of Before and After Periods
Vehicle speed data were collected over two separate time periods, the first period representing speed and compliance behaviour *before* the introduction of cameras, and the second period representing speed and compliance behaviour *after* camera introduction and issuance of speed camera traffic infringement notices.

The division of the data collection into two periods was based upon the introduction of Police enforcement of speed limits, using fixed-position camera technology. While it was the aim that the cameras were in place when the tunnel opened in April 2000, there was a lag in actual enforcement while necessary changes to legislation were implemented. This lag allowed for data collection to occur before offending drivers started receiving infringement tickets for their speeding behaviour. This represented the pre-implementation data collection phase. Changes to legislation were implemented in September 2000. This design procedure was justified based upon previous research conducted by the Monash University Accident Research Centre (Cameron, Cavallo and Gilbert, 1992, and Rogerson, Newstead and Cameron, 1994) that shows that it is the receipt of speeding tickets (Traffic Infringement Notices, or TINs) that leads to a reduction in crash numbers, rather than drivers simply seeing a speed camera at work.

Control Site
In addition to collecting speed data at camera locations both before and after camera operations had become prominent in the minds of drivers, a scientifically-rigorous study also requires corresponding speed measurements at one or more control sites. These additional speed data allow for estimates of the effects of speed cameras in the Domain Tunnel (1.6 kilometres in length) to be corrected for any extraneous effects of other, non-camera interventions or external influences that may affect speeds more generally across the road system.

A specific location along the route (i.e., on the Monash Freeway near the Yarra Boulevard exit ramp (i.e. WIMS[1] Station No. 2205)) was chosen as the control site. This site has three lanes at this point, matching with the three-lane configuration within the tunnel. Also, it is situated upstream from the camera locations, away from the Domain Tunnel, making it suitable for control measurement. Two camera systems were trialled initially by the Victoria Police, but only one system was used to enforce separately speeds in each of the three lanes of the tunnel.

Before Period
The Domain Tunnel opened to traffic in April 2000. Initially the speed limit in the tunnel was 60 km/h to allow tunnel users time to become familiar with the new situation. The speed limit became 80 km/h on about 3 May 2000. The *before* period was defined as the two weeks from 8th May 2000 to 21st May 2000[2]. During this time there was no actual enforcement of vehicle speeds in operation.

After Period
The *after* period was defined as the two weeks from 18th October to 31st October 2000. On 10th September 2000, the first round of speed camera media publicity was launched to alert drivers that traffic infringement notices would be issued for speeding in the tunnel. On 26th September 2000, the second round of speed camera publicity occurred through press and television coverage. Issuance of speed camera traffic infringement notices also commenced around mid-September 2000. Thus, this *after* period was chosen[3] to ensure that sufficient numbers of ticketed speeders would have received their infringement notices and would be travelling through the tunnel once again.

Measures of Effect
Speed profiles for each period were compared, using statistical methods (discussed below), to estimate speed camera technology effects on speed limit compliance in the tunnel. Comparisons of speed data were made both in aggregate and for particular circumstances. The study examined whether different impacts of speed camera technology occurred for different lane positions (left, middle or right lanes); days of the week (i.e., weekdays compared with weekend days); and hours of the day (i.e., peak periods compared with late night/early morning for weekdays and weekend days). The speed data examined provided information on statistically reliable changes from the *before* to the *after* periods after accounting for changes in corresponding speeds at the control site, in the following variables:

- Average vehicle speeds;
- Percentage of vehicles travelling over the speed limit (i.e. exceeding 80 km/h);
- Percentage of vehicles travelling over the enforcement threshold (i.e. exceeding 90 km/h), and
- Percentage of vehicles travelling at least 30 km/h over the speed limit (i.e. exceeding 110 km/h).

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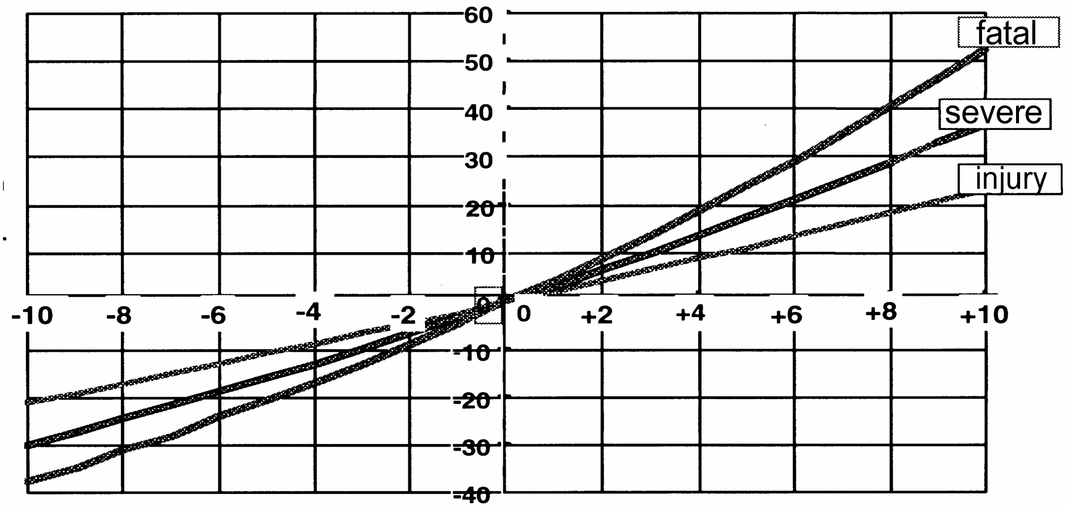
[1] Weigh-In-Motion System (WIMS) is a data collection method using vehicle detector loops embedded beneath pavement surfaces to measure vehicle speeds at specific locations, as well as measuring vehicle mass, length and number of axles, and classifying vehicles into one of 12 possible types (e.g., car, car/caravan, rigid truck, semi-trailer, etc.).
[2] *Before* data for the control site were available only up to 22nd May 2000.
[3] This *after* period was also partially chosen because control site data were *only* available for the 17th-31st October 2000.

Reductions in any one of these measures can reasonably be expected to lead to reduced crash and injury risk within CityLink tunnels. In particular, reductions in average vehicle speeds should have a significant impact on road safety in terms of the number of injury crashes, severe injury crashes and fatal crashes. This prediction is based upon well-established relationships reported in the road safety literature (e.g., Nilsson, 1984). According to these relationships, the outcome of a change in mean speed may be described in terms of power functions, with the size of the power increasing as crash severity increases. For example, the power function for fatalities is about four. Such a function leads to a substantial reduction in road trauma, even for a small reduction in mean speeds. The following graph (Figure 1), based on Swedish studies by Andersson and Nilsson (1997), illustrates these relationships. As can be seen from this graph, a 10% reduction in average speed leads to a 35-40% decrease in the number of fatal crashes. Figure 1 clearly illustrates the substantial effects of these power functions in terms of road trauma.

Figure 1 The predicted number of injury crashes, severe injury crashes and fatal crashes (y-axis) as a function of % changes in mean speeds (x-axis). The steepness of the curve increases with accident severity.



Variable Speed Limits

The speed limit applying within the Domain Tunnel was variable, ranging from a maximum of 80 km/h for normal conditions, to a lower limit of 40 km/h, depending upon traffic and safety considerations. This study addressed only those times when an 80 km/h speed limit applied in the tunnel. Other limits were not evaluated.

DATA AND METHODOLOGY

Vehicle Speed Data

For the analysis, speed data were collected to cover a two-week period, for each of the *before* and *after* periods. It was envisaged that a two-week period should provide sufficiently large samples for this study design. Table 1 depicts the number of vehicle speeds observed for both the Domain Tunnel and the control site (Yarra Boulevard) during the *before* and *after* periods, excluding data collected when the speed limit was lowered from 80 km/h during the after period (these observations constituted only about 3.5% of the total and are unlikely to influence the results).

In addition, there were some excessive vehicle speeds (i.e., over 200 km/h), assumed to have been incorrectly recorded at the control site during both the before- and after-periods. Since there were less than ten such observations recorded during each period, they were excluded from both the analyses and the Table 1 observations.

Table 1 Number of vehicle speeds observed at the Domain Tunnel and at the Yarra Boulevard Control Site during the Before and After Periods of the study

	TIME PERIOD	
SITE	**Before** (8th to 21st May 2000)	**After** (18th to 31st October 2000)
Domain Tunnel	316,254	413,061
Yarra Boulevard (Control)	522,475	581,783

Method of Analysis
Using suitable statistical analysis methods, speed data collected at both the camera locations and the control site were analysed to estimate the impact of speed camera technology on speed limit compliance. The analysis methods considered the effects of the cameras, taking into consideration changes in vehicle speeds that occurred at the control site. The changes in speeds (both as average speeds and as proportions exceeding the speed limit) that occurred after speed enforcement was implemented were compared with the speeds that occurred before enforcement. This estimate expressed as a *percentage change*, represents an initial effect of the speed camera enforcement.

Similarly, the percentage change in vehicle speeds (both for average speeds and for the proportion of speeds exceeding the limit) was estimated for the control site to measure the effects of factors other than speed camera enforcement that may affect vehicle speeds during the same before and after-periods.

To estimate the difference in the percentage change in vehicle speeds for the Domain Tunnel and the percentage change in vehicle speeds considered to be unaffected by the speed cameras in the tunnel (i.e., the control site speeds), a *net percentage change* was calculated. The *net percentage change* was considered to estimate the effect of the speed camera enforcement in the tunnel, after the effects of other factors have been taken into account.

The following methods were used to determine the statistical significance of the *net percentage changes* in speeds:

- Analysis of Variance techniques and general linear model analysis were applied to the data to determine if there had been a statistically significant change in *average vehicle speeds* after enforcement was implemented.

- Logistic regression and generalised linear model analyses were applied to the data to determine if there has been a statistically significant change in the proportion of vehicles exceeding the speed limit; the enforced speed limit, and 110 km/h in the Domain Tunnel after speed camera enforcement was implemented.

Though not presented in this paper, parallel analyses were also done *without* taking into account the changes in vehicle speeds that occurred at the control site. That is, the analyses only compared vehicle speeds in the tunnel before and after speed camera enforcement was implemented.

RESULTS
The findings summarised below considered the effects of speed cameras on vehicle speeds *after accounting for changes* in speeds at the control site chosen for the study. Initially, the effects were examined for the aggregated data, and later analysed distinguishing between lane-position, time of day and day of week of vehicle travel.

Aggregate Findings: Average Vehicle Speeds and Proportions Exceeding Limit
The aggregate findings of the study indicate that fixed speed cameras in the Domain Tunnel have been effective in significantly reducing average vehicles speeds as well as in reducing the proportion of drivers not complying with the speed limit ($p<0.01$). Some of these findings are also depicted graphically in Figures 2 and 3.

- After implementation of speed enforcement in the Domain Tunnel, average vehicle speeds significantly reduced by a net *3.4%* from 75.05 km/h to 72.50 km/h. This net percentage reduction took into consideration the changes in average vehicle speeds that occurred at the control site during the same before and after periods.

- Reductions in average vehicle speeds should have a significant impact on road safety in terms of the number of injury crashes, the number of serious injury crashes and the number of fatal crashes. This prediction is based upon the relationships reported in the road safety literature (i.e., Nilsson, 1984). Using Nilsson's power-function relationships, the net 3.4% reduction in average vehicle speeds that occurred after implementation of speed enforcement, can be translated as resulting in an estimated 13% reduction in fatal crashes; a 10% reduction in serious injury crashes and a 7% reduction in injury crashes. Figure 2 displays these reductions.

- The proportion of drivers whose *vehicle speeds exceeded 80 km/h* significantly reduced after speed camera enforcement by a net 66% from 1,747 per 10,000 drivers to 596 per 10,000 drivers.

- The proportion of drivers whose *vehicle speeds exceeded 90 km/h* significantly reduced after camera enforcement by a net 79% from 184 per 10,000 drivers to 38 per 10,000 drivers.

- The proportion of drivers whose *vehicle speeds exceeded 110 km/h* significantly reduced after camera enforcement by a net 76% from 47 per 100,000 drivers to 11 per 100,000 drivers.

It should be noted that all of the above net % reductions were statistically reliable, with statistical significance achieved at above the 99% level (i.e., $p<0.01$).

Figure 2. Estimated reduction in fatal, serious injury and all injury crashes, associated with the net 3.4% reduction in average vehicle speed that occurred after speed camera enforcement in the CityLink Domain Tunnel

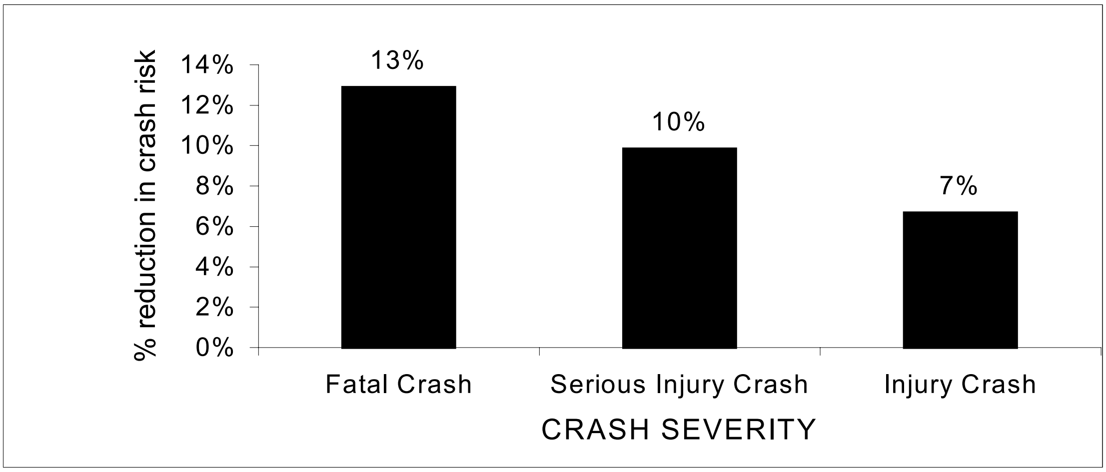
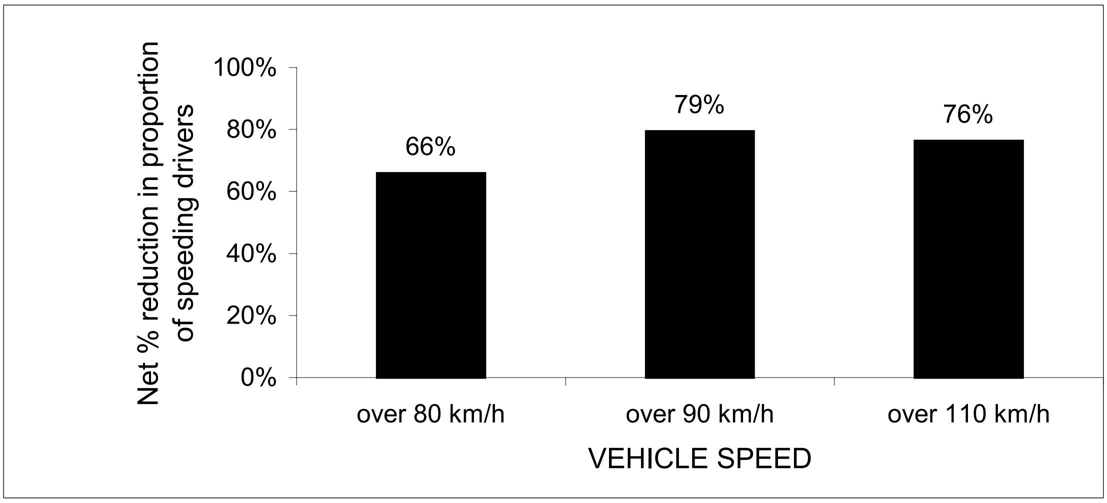


Figure 3. Net % reduction in the proportion of drivers exceeding 80 km/h, 90 km/h and 110 km/h after speed camera enforcement in the CityLink Domain Tunnel



Effects of Cameras by Lane Position

The findings of the 'lane' analysis indicate that the fixed speed cameras in the Domain Tunnel have been effective in significantly reducing average vehicle speeds and reducing the proportion of drivers not complying with the speed limit for *each lane* in the tunnel ($p<0.01$). The largest reductions were found for vehicles travelling in the *left lane* (average speeds fell by 4.1%), and the smallest reductions for those travelling in the *right lane* (average speeds fell by 2.2%). This beneficial result was evident for all measures of effect, i.e. average vehicle speeds, the proportion of drivers/riders exceeding the speed limit, exceeding 90 km/h and exceeding 110 km/h.

Effects of Cameras According to the Day of Week

The effects of the speed camera enforcement were examined according to the *day of week* of travel, namely, weekday travel (i.e. Monday to Friday) and weekend day travel (i.e. Saturday and Sunday). The findings indicate that the fixed speed cameras in the tunnel have significantly reduced average vehicle speeds and the proportions of drivers exceeding 80 km/h, 90 km/h and 110 km/h on *both weekdays and weekend days* ($p<0.01$). The reductions were significantly larger on weekends when considering the average vehicle speeds and the proportion of drivers exceeding the speed limit as the measures of effect. Reductions in average speeds of 5.4% were found for Saturday-Sunday and 2.9% for Monday-Friday. The proportions of drivers with vehicle speeds *exceeding 80 km/h, 90 km/h and 110 km/h* on Saturday-Sunday fell by a net 68 - 79% and on Monday-Friday by a net 65 - 80%;

Time of Day Effects

The effects of the speed camera enforcement were examined according to the time of day of travel for both weekdays and weekend days. While Diamantopoulou and Corben (2001) set out more completely the results of the time of day analyses, the main findings are that the speed camera technology has been most effective in reducing vehicle speeds on **weekdays in afternoon peak periods**, though no clear time-of-day pattern is evident for weekends. During the *afternoon peak period on weekdays* the camera technology significantly reduced ($p<0.01$):

- Average vehicle speeds by a net 5.6% from 76.3 km/h to 71.9 km/h, and
- The proportion of drivers exceeding the speed limit of 80 km/h, the enforcement threshold of 90 km/h and the extreme speeding threshold (i.e. >30 km/h above the limit) by a net 74%, a net 89% and a net 89%, respectively.

DISCUSSION AND CONCLUSION

Based on full sampling of vehicle speeds over two-week before- and after-periods, both within the Domain Tunnel and at an upstream control site, it is concluded that the fixed-position, automated speed camera technology successfully reduced speed-related crash and injury risk in the tunnel. Specifically, the camera technology has:

- Reduced average vehicle speeds by 3.4%, from 75.05 km/h to 72.50 km/h, resulting in an estimated reduction in fatal, serious injury and injury crash risk of 13%, 10% and 7%, respectively;
- Reduced the proportions of drivers exceeding the speed limit of 80 km/h, the enforcement threshold of 90 km/h and the extreme speeding threshold (i.e. >30 km/h above the limit) by 66%, 79% and 76% respectively;
- Been more effective in reducing vehicle speeds in the left than in the right lane (i.e., 4.1% reduction, c.f. 2.2%);
- Been more effective in reducing vehicle speeds on weekends than on weekdays (i.e. 5.4% reduction c.f. 2.9%)
- Been most effective in reducing vehicle speeds on weekdays in afternoon peak periods.

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