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ON THE SPEED REDUCTION POTENTIAL OF PILOT VEHICLE USE IN WORK ZONES

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ABSTRACT

Despite significant research efforts to understand the speed reduction potentials of work zone interventions, little is known about the reductions achievable by the use of pilot vehicles. This paper innovatively examines the speed reduction potential of pilot vehicle in a Queensland rural highway work zone. Analysis of five days' speed data showed that pilot vehicle reduced mean speeds at the treatment location, but not downstream. The proportion of speeding vehicles was also reduced, particularly those travelling at 10 km/h or more above the posted limit. Motorists were more likely to speed during the day, under a 40 km/h limit and when traffic volumes were higher. While it is commonly believed that pilot vehicle controls the speeds of all following vehicles, results of this study showed that pilot car had greater effects on reducing speeds of vehicles following it closely than those which are far behind in a traffic stream. To maximize these benefits, it is necessary to ensure that the pilot vehicle itself is not speeding.

Keywords: Pilot car, roadwork safety, speeding, speed reduction, Work zone safety.

INTRODUCTION

Noncompliance with posted speed limits in work zones has been identified as a serious safety concern worldwide (e.g., Garber and Srinivasan, 1998, Allpress and Leland Jr, 2010, Arnold Jr, 2003, Debnath et al., 2015). Research in Queensland, Australia (Debnath et al., 2014) showed that almost all drivers (77-98%) drove over posted speed limits when approaching a roadwork zone, while many (19-45%) drove at 20 Km/h or more over the posted limits. Similarly for the areas inside roadwork zones, where roadworkers and machinery are usually located, 66-89% of drivers were reported driving over the posted limits. Consistent with these statistics, a state-wide survey of truck drivers in Illinois (Benekohal and Shim, 1999) found that half of the respondents admitted to exceeding work zone speed limits despite 90% considering that work zones were more hazardous than regular road sections. Drivers are likely to drive at speeds they perceive to be suitable, or with which they are comfortable, regardless of the posted limits (Haworth et al., 2002, Brewer et al., 2006). As the lowest speeds are usually observed in the active work area (Debnath et al., 2014), speeding behaviour depends somewhat on the actual work activities occurring (or perceived to be occurring) in different sections of a work zone.

A wide range of measures are used to reduce speeding in work zones and their effectiveness has been the subject of considerable research. In a recent review of this literature, Debnath et al. (2012) classified the measures into four categories: informational, physical, enforcement, and educational measures. Among the informational measures, static speed limit signs were found to generally reduce speeds but did not bring speeds down to posted limits (Haworth et al., 2002, Benekohal et al., 1992). Advance warning signage was found to have no effect on speeds (Huebschman et al., 2003), but variable message signage (VMS) (Garber and Srinivasan, 1998, Brewer et al., 2006) and VMS with speed feedback (Maze et al., 2000, Fontaine et al., 2000) reduced speeds significantly. Driver warning systems (e.g., in-vehicle visual and audio warnings, emergency flasher traffic control device) were also found to improve drivers' compliance with speed limits (Whitmire II et al., 2011, Bai and Li, 2011). Studies examining physical measures, such as rumble strips (Fontaine and Carlson, 2001, Meyer, 2000) and optical speed bars (Meyer, 2004) produced inconsistent findings, but these measures appeared to have relatively small effects on speeds and were ineffective for transient and moving work zones. Enforcement was found to be the most effective of all measures. The presence of speed cameras (Huebschman et al., 2003, Hajbabaie et al., 2009) and police cars with flashing lights (Hajbabaie et al., 2009, Huebschman et al., 2003, Arnold Jr, 2003) in work zones significantly improved speed limit compliance, although the effects were often temporary and localized. Imposing higher fines for violating speed limits in work zones appeared to have little effect on speeds (Ullman et al., 2000). Formal evaluations of educational measures are lacking in the literature, but many (e.g., Arnold Jr, 2003, Haworth et al., 2002) have argued that educational and awareness campaigns are likely to be effective when used in conjunction with enforcement initiatives.

Despite the many studies evaluating the effectiveness of speed control measures in work zones, the effectiveness of pilot vehicle operation has not been examined. A pilot vehicle is typically driven by roadwork traffic control personnel in order to guide traffic through a roadwork site while regulating the speeds of travelling vehicles. Use of pilot vehicles is among the methods prescribed in the Manual on Uniform Traffic Control Devices (MUTCD) used in Queensland (Queensland Government, 2010) to coordinate one-way movements in work zones when a single lane is open to two-way traffic. The MUTCD states that pilot vehicles are required to guide traffic through static work zones when a) part of the work zone is out of view of the supervisor/traffic controller, b) the posted speed limit is less than 40 km/h due to the presence of hazards to workers, c) speed is required to be kept low to minimize damage to works, or d) the travel path is not obvious to follow. In addition to these requirements, a pilot vehicle must carry a vehicle mounted warning device (single/pair of yellow beacon lamps or an illuminated flashing arrow sign) and traffic should be instructed, either verbally or by means of signage, to follow and not to overtake pilot vehicle.

The emergency flasher traffic control device (EFTCD) evaluated by Bai and Li (2011) is the safety measure most similar to a pilot vehicle in terms of operational characteristics. However, the use of an EFTCD differs significantly from the use of a pilot vehicle. EFTCDs are used by drivers of public vehicles, whereas a pilot vehicle is driven by a trained operator who has prior and proper knowledge about the work zone. Moreover, a public vehicle equipped with EFTCD may choose not to drive within posted speed limit, but a pilot vehicle is used to keep motorists' speeds within posted limits or at a safe level. In an older study, Burritt and Guenther (1987) used two pilot vehicles (one at the beginning of the traffic queue and the other at the end) to develop a relationship between approach volume and maximum service flow rate. However, there were no quantitative comparisons between the presence and absence of pilot vehicle operation, or examinations of the speed reduction effects of the pilot vehicles. As this gap in the literature suggests, the effectiveness of pilot vehicles in reducing travel speeds is not well understood.

While it is commonly believed that pilot vehicles control the speed of all vehicles following a pilot vehicle because the follower vehicles are unable to overtake the pilot vehicles, a scientific examination of the speed reduction potential of pilot vehicles is lacking in the literature. Consequently, it remains unknown if the common belief about pilot vehicles is true or if the effects of pilot vehicles vary among the follower vehicles depending on how closely they follow the pilot vehicles. In addition, it is not known if pilot vehicles produce any effects on the speeds of vehicles 'downstream' of the area where pilot vehicle operates. Typically pilot vehicles escort public traffic from the start of the work area to the end of the work area, where the lowest speed limits are present. At the end of the work area, pilot vehicles pull over to the side of the road and public traffic are allowed to travel to the termination area of roadwork sites without pilot vehicle escort. Once all of the public traffic, which were escorted by the pilot vehicle, pass the pilot car it makes a U-turn to escort the public traffic travelling to the other direction. Understanding the downstream effects is important as drivers might attempt to increase their speeds after passing a pilot vehicle in order to compensate for the extra travel time experienced due to following a pilot vehicle upstream.

This paper aims to fill these important gaps in the literature by innovatively examining the effectiveness of pilot vehicle operation in a long-term one-lane two-way work zone. To achieve this objective, travel speeds for five consecutive days at a work zone situated on a normally two-lane, two-way rural highway in the state of Queensland, Australia were analysed. Analyses focused on examining the speed reduction effects of pilot vehicle operation within the work zone, as well as at a downstream location for halo effects. The study method, including the data collection process and analysis techniques, is presented in the following section, followed by presentation of the results and discussion of the findings, before finally concluding the paper.

METHOD

Experimental setting

This study was conducted in a long-term 4.1 km work zone on a rural highway (Bruce Highway), which is the major transport route servicing north-eastern Australia. Work was conducted over seven months, with data collection commencing about five months into this period and two months before project completion. The highway at this point is a sealed one lane each way undivided road with pre-work zone speed limits of 100 km/h at the southern end and 80 km/h at the northern end. This stretch of road is straight and mostly flat with good sight distance. A schematic diagram of the work zone showing the posted signage and the location of speed measurement points is presented in Figure 1.

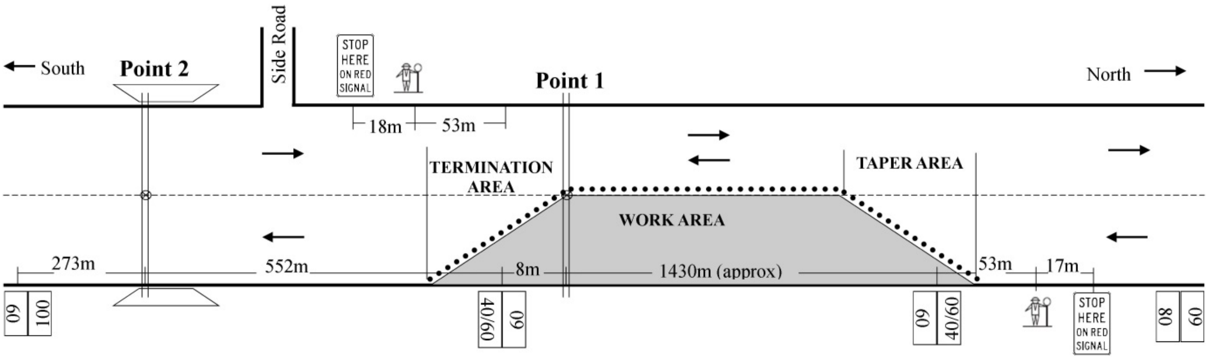

Figure 1. Plan of work zone

Work involved full closure of one lane within the work area for the purpose of resurfacing, with the closed lane alternating as required. The direction of traffic was alternated by manual traffic control with temporary traffic lights. Standard sets of signage following the MUTCD used in Queensland (Queensland Government, 2010) were placed at both ends of the work zone starting with ‘Road Work Ahead/Reduce Speed/80km/h’ followed by ‘Reduce Speed/60km/h’, and ‘Prepare to Stop/Do Not Overtake’ signs at respective 300 meter intervals. A ‘Standard roadworker sign’ coupled with ‘Reduce Speed/40km/h’ was placed at both ends of the taper and termination areas with repeated signs at every 300 meters within the work area. South-bound traffic was stopped at the northern end of the work zone 44 meters before the start of the taper area by a traffic controller using portable traffic lights. Another traffic controller with a stop/slow bat was placed at an upstream location to prevent vehicles from queuing on a bridge located near the work zone. Using similar methods, the north-bound traffic was stopped 42 meters before the start of the termination area at the other end of the work zone.

Figure 2. Pilot vehicle in operation

A pilot vehicle (Figure 2) was used to control the speed of public vehicles through the closed lane section of the work zone during the daytime working hours (generally 0600-1800 hours). The pilot vehicle carried windscreen-mounted and side-mounted flashing amber lights, and a top-mounted VMS displaying alternating amber lights to the rear. The pilot vehicle guided traffic within the taper area and the termination area only. Traffic controllers at both ends used radios to inform each other about the last public vehicle in the queue (usually by its colour, make, and/or model).

Speed data for the south-bound traffic were collected at two points: at the work area in the southern end of the work zone (Point 1) and at a location 560 meters downstream of the first point (Point 2). Distances of Point 1 from the locations where traffic was stopped at the southern end (1500 meters) and northern end (79 meters) of the work zone suggests that the north-bound traffic (including the pilot vehicle) might not have reached at their desired speeds of travel when crossing the tubes at Point 1 starting from a complete stop at traffic control. On the other hand, the large distance for the southbound traffic would allow the pilot vehicle to reach its desired speed of travel at Point 1. Therefore, the focus of the study is limited to the south-bound traffic only.

Speed data from both lanes were collected using pairs of pneumatic tubes installed 1 meter apart on the pavement and connected to Metrocount Vehicle Classification System. Data for five consecutive days (Wednesday 0845 hours to Sunday 2400 hours) was analysed. The pilot vehicle was present during the daytime hours of Thursday to Saturday. Workers were present in the closed lane and on the shoulder from Wednesday to Saturday during the daytime hours when the posted speed limit was 40 km/h in the work area (the limit was 60 km/h during the night hours). Wet surface due to rain precluded work on Sunday and a 60 km/h speed limit was posted throughout the day and night hours. The posted speed limit at Point 2 was 60 km/h for the entire data collection period.

Data

Speed, headway (distance between front bumpers of two vehicles), gap (clear distance between two vehicles), type of vehicle, and time were collected for each vehicle which passed over the tubes. Vehicles were classified using the ARX vehicle classification scheme, which classifies vehicles into three aggregate classes: Light vehicles (Very short – bicycle, motorcycle; Short – sedan, wagon, 4WD, utility, light van; Short towing – trailer, caravan, boat etc.), Medium vehicles (two and three axle bus or truck, four axle truck), and Heavy vehicles (articulated vehicle or rigid vehicle and trailer with more than two axles, B-double or heavy truck and trailer, double or triple road train or heavy truck and more than one trailer). Data was collected and analysed in Metric units (e.g., speed in km/h, gap in meters).

Individual vehicle data were extracted by running ‘Individual vehicle reports’ from the Metrocount software. Separate datasets were obtained for the two data collection points. A rigorous data cleaning process was then undertaken to identify and remove the data points which might be erroneous. Firstly, the data points with zero headway, which were reflected in the individual vehicle reports with the label “coerced sequence”, were removed from the datasets. About 8.5% (n =1493 out of 17659) and 0.22% (n = 37 out of 16957) of the data points were removed at Point 1 and 2, respectively. Secondly, the observations where a vehicle was heading north were removed to obtain only the south-bound observations. Finally, observations of pilot vehicle and work vehicles (where identifiable) were separated from the public vehicle observations in the Point 1 dataset. A pilot vehicle is usually the first vehicle in a traffic queue, with exception in some cases where a work vehicle was ahead of the pilot vehicle. Such cases and the exceptions were identified by examining the types of vehicles (a pilot vehicle is a light vehicle) and headways of successive vehicles. For instance, if two vehicles at the front of a queue have large headways and the third vehicle has small headway, it is likely that the second vehicle is the pilot vehicle and the first one is a work vehicle. It should be noted that Point 2 was away from the pilot vehicle operation area; therefore, separation of such data was not required for Point 2. The final datasets after the cleaning exercise included 15,285 and 16,618 observations for Point 1 and Point 2, respectively.

Statistical Analyses

A three-step approach was undertaken to analyse the datasets. In the first stage, the Point 1 data were analysed descriptively to calculate the differences in mean speeds and proportion of speeding vehicles when a pilot vehicle was in operation and when it was not. Effects of the pilot vehicle on speed reduction for different types of vehicles were also examined. Since the posted speed limit during pilot vehicle operation was 40 km/h, only the observations under the same limit are included in this stage of the analysis.

While this stage provides a quick and direct comparison of speeds in the presence and absence of the pilot vehicle, it is important to note that motorists' speeds do not necessarily depend only on the presence of the pilot vehicle: characteristics of the work zone and traffic are likely to affect the speeds as well. Therefore, in the second stage, a regression model was developed to model the probability of a public vehicle speeding (i.e., speed of public vehicle is above the posted speed limit) in order to examine how presence of the pilot vehicle and other characteristics of the work zone and traffic affect this probability. The two categories of a public vehicle's speed (speeding or not speeding) can be well formulated in the form of a binary logistic model as

$$y_i^* = \boldsymbol{X}_i\boldsymbol{\beta} + \varepsilon_i \tag{1}$$

$$y_i = \begin{cases} 1\ if\ y_i^* > 0\ (speeding) \\ 0\ if\ y_i^* \leq 0\ (not\ speeding) \end{cases} \tag{2}$$

where y_i^* is a latent variable ranging from $-\infty$ to ∞ measuring the observed outcome variable y_i using eq. 2; y_i is the observed speed of public vehicle *i* categorized into two classes: speeding and not speeding; $\boldsymbol{X}$ is a vector of explanatory variables; $\boldsymbol{\beta}$ is a vector of regression coefficients; and ε_i is the regression error term. A set of explanatory variables describing the characteristics of the work zone and traffic (see Table 2) which were assumed to be associated with the probabilities of public vehicles travelling above the posted speed limits were included in the model. To estimate the parameters, the model was fitted using the 15,285 observations of Point 1.

The third stage involved examining the downstream effects of pilot vehicle operation by comparing mean speeds and proportions of speeding vehicles at Point 2 under the conditions of presence and absence of the pilot vehicle in the upstream work area. The pilot vehicle was present only during the day (0600-1800 hours) but the speed limit was 60 km/h at Point 2 during both day and night. Therefore, the downstream effects were analysed separately for day and night periods to examine if the patterns differ.

RESULTS

Effects of pilot vehicle in work area

The speed profile of all vehicles (average speeds in 15 minute intervals) at the work area in the work zone along with posted speed limits is shown in Figure 3. All days except the last day of data collection had posted limits of 40 km/h during the daytime hours (0600-1800) and

60 km/h during the night-time hours (1800-0600). The last day of data collection, when no work was undertaken because of the wet surface, had a 60 km/h limit for both day and night-time hours. The speed profile of the remaining days shows that the average speeds were generally above the posted limit during the daytime hours, but were under the limit during the night-time hours. This indicates that there is higher prevalence of speeding in daytime than at night. On the last day, average speeds were around the posted limit, but dropped significantly during the morning hours, possibly because of rainfall in the morning. All of the 15 minute blocks had some speed observations except one, which is shown as zero average speed.

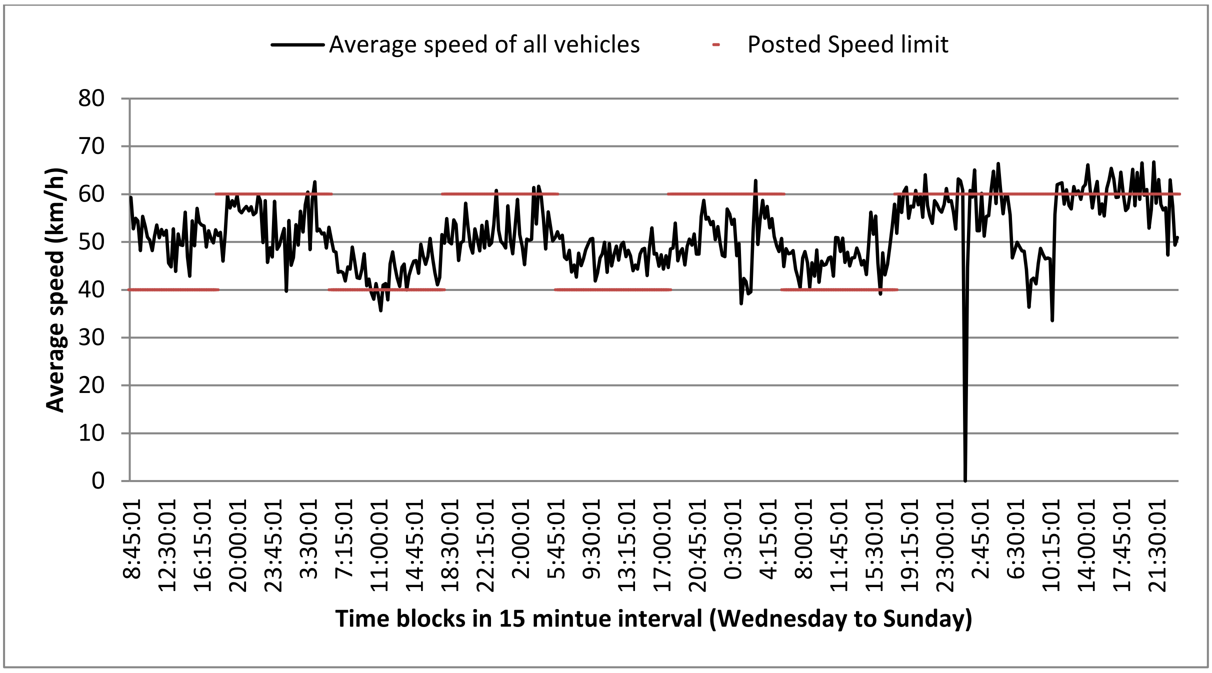

Figure 3. Average speed profile of all vehicles in 15 minute intervals

Table 1 presents the mean speeds and proportions of vehicles speeding with and without pilot vehicle operation in the work area (Point 1), both aggregately and separately for different types of vehicles. The mean speed of all vehicles under a posted speed limit of 40 km/h was 5.9 km/h lower (dropped from 52.0 to 46.1 km/h) when a pilot vehicle was present. The size of the reduction did not differ significantly by type of vehicle. Despite these reductions, the mean speed of all vehicles remained 6.1 km/h above the posted limit when the pilot vehicle was in operation.

Under pilot vehicle operation, the proportion of vehicles travelling above the posted limit fell by 12.5%. Almost all vehicles (97.8%) violated the posted limit in the absence of the pilot vehicle, whereas 85.3% did so when it was present. The largest reduction in prevalence of speeding was seen for medium vehicles (15.0%), followed by heavy (12.8%) and light vehicles (12.1%). The effect of the pilot vehicle in reducing speeding vehicles was greater (32.7%) in the case of travelling at least 5 km/h above the posted limit. Similar patterns of reductions were seen for the three types of vehicles. Despite these reductions, 55.7% vehicles (again with a smaller share of medium vehicles) still travelled at least 5 km/h above the limit.

The greatest reduction occurred in the proportion of vehicles travelling at least 10 km/h over the limit (38.1%) with a greater reduction for medium vehicles (40.4%) than the light (37.9%) and heavy vehicles (37.8%). For the three cases (proportion of vehicles speeding, speeding by 5km/h, and speeding by 10 km/h), operation of the pilot vehicle had the greatest effect on medium vehicles. However, in the case of travelling at more than 15 km/h above the posted limit, operation of the pilot vehicle had more effects on light vehicles in reducing the proportion of speeding vehicles than on medium and heavy vehicles.

It is important to know the speed profile of the pilot vehicle in order to evaluate its speed reduction ability. In a total of 162 trips made by the pilot vehicle during the study period, it travelled at a mean speed of 38.1 km/h (S.D. = 4.6). It exceeded the posted 40 km/h limit on 34% of its trips, and exceeded the limit by 5 km/h or more on 7.4% of the trips. The result that the pilot vehicle was speeding in some cases was found only after the analysis of the data was done, therefore, it was not possible to investigate the reasons why the pilot vehicle was speeding on site. Future research may include surveys with drivers of pilot vehicles in order to investigate the probable reasons.

Table 1. Effects of pilot vehicle in work area

	Pilot vehicle present											
	No				Yes				Reduction (No - Yes)			
Type of vehicle (No of obs.)	All (2271)	Light (1675)	Medium (265)	Heavy (331)	All (7977)	Light (6107)	Medium (834)	Heavy (1036)	All	Light	Medium	Heavy
Mean speed (km/h)	52.03	52.12	51.35	52.11	46.13	46.22	45.28	46.33	5.90	5.90	6.07	5.78
Standard Dev. of mean speed	6.23	6.25	6.69	5.67	5.84	5.79	6.13	5.86	NA	NA	NA	NA
% vehicle speeding	97.75	98.03	95.09	98.49	85.27	85.90	80.10	85.71	12.48	12.13	15.00	12.78
% vehicle speeding by 5 km/h	88.46	88.42	85.28	91.24	55.72	56.31	49.28	57.43	32.74	32.11	36.00	33.81
% vehicle speeding by 10 km/h	62.92	62.81	61.89	64.35	24.78	24.94	21.46	26.54	38.14	37.87	40.42	37.81
% vehicle speeding by 15 km/h	30.74	31.46	27.92	29.31	7.58	7.61	6.71	8.11	23.15	23.85	21.21	21.20
% vehicle speeding by 20 km/h	9.82	10.21	8.30	9.06	1.24	1.16	1.56	1.45	8.58	9.05	6.74	7.62

Regression model results

To model the probability of a public vehicle speeding under pilot vehicle operation, it is necessary to define the response variable according to the speed pattern of the pilot vehicle. This is because the pilot vehicle set the highest possible speed for the vehicles following it. Since that the pilot vehicle was speeding in some trips (but mostly by 5 km/h over the posted speed limit), the response variable of the regression model is defined as ‘a public vehicle speeding at least by 5 km/h’ (= 1) and ‘not-speeding’ (= 0). Pairwise correlations of all explanatory variables were tested which showed no significantly correlated variables (correlation coefficient of 0.5 or more) in the model.

Table 2. Explanatory variables and regression estimates

Explanatory variable	**Description**	**Beta**	**O.R.**	**p value**
Time of day				
00:01 - 03:00	If yes = 1, otherwise = 0	-0.338	0.713	0.257
03:01 - 06:00	If yes = 1, otherwise = 0	-0.453	0.636	0.018*
06:01 - 09:00	If yes = 1, otherwise = 0	0.186	1.204	0.007*
09:01 - 12:00#	If yes = 1, otherwise = 0			
12:01 - 15:00	If yes = 1, otherwise = 0	0.159	1.172	0.004*
15:01 - 18:00	If yes = 1, otherwise = 0	0.160	1.174	0.009*
18:01 - 21:00	If yes = 1, otherwise = 0	-0.576	0.562	<0.001*
21:01 - 24:00	If yes = 1, otherwise = 0	0.095	1.100	0.618
Presence of workers in work zone				
No	If absent = 1, otherwise = 0	0.321	1.379	0.001*
Yes#	If present = 1, otherwise = 0			
Work break	If in work break = 1, otherwise = 0	-0.770	0.463	<0.001*
Posted speed limit	If 40 km/h = 1, 60 km/h = 0	4.512	91.132	<0.001*
Presence of Pilot vehicle	If present = 1, otherwise (absent) = 0	-1.921	0.146	<0.001*
Type of vehicle				
Light vehicle#	If MC, SV, or SVT = 1, otherwise = 0			
Medium vehicle	If TB2, TB3, or T4 = 1 , otherwise = 0	-0.252	0.777	<0.001*
Heavy vehicle	If ART3, ART4, ART5, ART6, BD, or DRT = 1 , otherwise = 0	-0.084	0.920	0.189
Traffic volume^	Number of vehicles in traffic stream	0.009	1.009	<0.001*
Proportion of large vehicles^	% of medium and heavy vehicles	-0.018	0.983	<0.001*
Gap (from front vehicle)				
<=2 seconds#	If gap <=2 secs = 1, otherwise = 0			
2.1 - 4 seconds	If gap 2.1-4 secs = 1, otherwise = 0	0.221	1.247	<0.001*
4.1 - 8 seconds	If gap 4.1-8 secs = 1, otherwise = 0	0.606	1.833	<0.001*
8.1 - 14 seconds	If gap 8.1-14 secs = 1, otherwise = 0	1.134	3.107	<0.001*
>14 seconds	If gap >14 secs = 1, otherwise = 0	0.666	1.946	<0.001*
Number of observations		15285		
Log-likelihood (constant term only)		-10523.09		
Log-likelihood (calibrated model)		-7515.55		
Akaike Information Criteria (AIC)		15071.1		
Likelihood ratio statistics (G^2)		6015.08	(19 *df*)	<0.001

Reference category; ^ measured in 15 minute block around the time when a vehicle's speed is measured;
* significant at 99% confidence level

The parameters of the binary logistic model were derived using the maximum likelihood estimation method in the software STATA 11.2. The parameter estimates, odds ratios (O.R.), and their statistical significance are presented in Table 2. The fitted model produced an Akaike Information Criteria (AIC) value of 14985 and likelihood ratio statistics of 6101.2 (19 *df*), which is well above the corresponding critical value for significance at the 1% level, implying that the model has sufficient explanatory power. The estimation results of significant variables are discussed in the following paragraph.

A public vehicle is more likely to travel at 5 km/h or more above the posted speed limit (40 km/h) during daytime hours (6am-9am, O.R. = 1.20; 12pm-3pm, O.R. = 1.17; and 3pm-6pm, O.R. = 1.17) and less likely during the evening and night hours (6pm-9pm, O.R. = 0.56 and 3am-6am, O.R. = 0.64) relative to the 9am-12pm period. The estimates for the hours between 9pm-3am were not statistically significant.

The odds of speeding were 37.9% higher when workers were not present and were 53.7% lower when workers were having a break. Vehicles were more likely to speed when the posted limit was 40 km/h (O.R. = 91.13) than when it was 60 km/h. Presence of the pilot vehicle was associated with 85.4% lower odds of a vehicle speeding.

In comparison to light vehicles, medium vehicles were less likely to speed (22.3% lower odds), but the result for heavy vehicles was not statistically significant. The likelihood of vehicles speeding was found to increase with increasing traffic volume (O.R. = 1.01) and to decrease with an increase in the proportion of medium and heavy vehicles (O.R. = 0.98). Both of these variables were defined in 15 minute blocks around the time when the vehicle's speed was measured.

Relative to the vehicles with a small gap to the vehicles in front (<= 2 seconds), vehicles with higher gaps were more likely to speed. The odds of a vehicle speeding were 24.7% higher when the gap was 2.1 to 4 seconds, 83.3% higher when the gap was 4.1 to 8 seconds, and 94.6 % higher when the gap was greater than 14 seconds. The highest odds (210.7% higher than the case of <= 2 seconds gap) were found for vehicles with gaps of 8.1 to 14 seconds.

Table 3. Downstream effects of pilot vehicle

Type of vehi-cle	Time	Pilot vehicle present	No of obs.	Mean speed (km/h)	% vehicles speeding	% vehicles speeding by 5 km/h or more	% vehicles speeding by 10 km/h or more	% vehicles speeding by 15 km/h or more	% vehicles speeding by 20 km/h or more
All vehicles	Day	Yes	8557	61.59	62.05	31.23	11.15	2.89	0.88
		No	4886	62.29	62.73	36.45	17.58	8.33	4.20
		No-Yes*		0.70	0.68	5.23	6.43	5.44	3.32
	Night	No	3175	71.56	91.69	77.67	54.71	32.38	17.01
Light vehicles	Day	Yes	6738	61.88	62.67	31.92	11.74	3.12	0.95
		No	3915	62.7	64.55	37.65	17.47	7.84	3.75
		No-Yes*		0.82	1.87	5.73	5.73	4.72	2.80
	Night	No	2186	71.38	92.09	77.04	53.93	31.24	15.46
Mediu m vehicle	Day	Yes	573	59.79	57.24	26.70	9.08	1.57	0.35
		No	359	59.7	52.92	27.30	15.60	10.31	5.85
		No-Yes*		-0.09	-4.32	0.60	6.52	8.74	5.50

	Night	No	184	72.26	89.67	76.09	60.87	38.59	24.46
Heavy vehicles	Day	Yes	1246	60.83	60.91	29.53	8.91	2.25	0.72
		No	612	61.17	56.86	34.15	19.44	10.29	6.05
		No-Yes*		0.34	-4.05	4.62	10.54	8.05	5.32
	Night	No	805	71.91	91.06	79.75	55.40	34.04	19.50

* Difference between the cases ‘No’ and ‘Yes’ for each type of vehicle during day hours

Downstream effects

Table 3 summarizes the effects of the pilot vehicle at a downstream location (Point 2), both aggregately and separately for different types of vehicles. The mean speeds during daytime with and without pilot vehicle operation were similar, suggesting that the pilot vehicle had no significant effects on downstream speeds. However, the night-time speeds (when the pilot vehicle was not present) were higher than the day speeds in the presence of the pilot vehicle.

During daytime at Point 2, the proportion of light vehicles travelling above the posted limit was 1.9% lower when the pilot vehicle was in operation compared with when it was not. On the other hand, the prevalence of speeding increased by 4.3% and 4.1% for medium and heavy vehicles respectively. However, these increases were not reflected in trends for travel at a significantly higher level above the speed limit. When the proportions of vehicles speeding by at least 5 km/h or more above the limit were compared, none showed evidence of increase. The greatest reduction for medium vehicles was observed in the case of vehicles speeding by at least 15 km/h above the limit (8.7%), followed by when vehicles were speeding by at least 10 km/h above the limit (6.5%). For heavy vehicles, the highest reductions were for vehicles speeding by at least 10 km/h (10.5%) and by at least 15 km/h (8.1%). For light vehicles, greater effects were observed for smaller margins above the limit than in the cases of medium and heavy vehicles. Both the cases where vehicles were speeding by at least 5 km/h or 10 km/h saw a reduction of 5.7%.

DISCUSSION

In the work area, the average speed of vehicles was reduced when a pilot vehicle was present and the reductions were similar for different types of vehicles. However, the average speed remained about 6 km/h above the posted limit when the pilot vehicle was present. These findings imply that the pilot vehicle effectively reduced travel speeds when in operation, but did not necessarily confine the speeds to within the posted limit.

The effectiveness of the pilot vehicle in bringing down speeds could have been restricted by the failure of the pilot vehicle to always obey the posted speed limit. The pilot vehicle exceeded the posted speed limit on one-third of its trips, and by 5 km/h on 7.4% of trips. Since a pilot vehicle leads and guides the public traffic stream through the work zone, the maximum speeds of the public vehicles, particularly those which are in the traffic stream immediately behind the pilot vehicle, will be influenced by the speed of the pilot vehicle. When the pilot vehicle travelled at a speed higher than the limit, the public vehicles following the pilot vehicle were likely to travel at a similar speed. Therefore, the excess speeds of the pilot vehicle above the limit arguably contributed to the 6 km/h excess in the mean speed of all vehicles. Furthermore, the excess speed could also be observed due to the higher speeds of the vehicles which joined the traffic stream with higher gaps between them and their leading vehicles. Results showed that vehicles with higher gaps have a greater likelihood of speeding since these vehicles have more opportunity and room to accelerate and catch the traffic stream immediately behind the pilot vehicle. Therefore, it is reasonable to argue that a pilot vehicle has more effect on the speeds of vehicles following it closely than on the speeds of those which are far behind.

In addition to reducing mean speeds, the presence of the pilot vehicle also reduced the proportion of vehicles exceeding the posted speed limit. While in the absence of the pilot vehicle almost all vehicles (98%) violated the speed limit, about 85% still did in its presence. The pilot vehicle had a much larger effect on the proportions of vehicles exceeding the speed limit by 5 km/h or more or 10 km/h or more (33% and 38% reductions, respectively). Thus, the pilot vehicle effectively reduced the number of vehicles travelling at particularly risky speeds.

While the pilot vehicle significantly reduced speeding by all types of vehicles, there were larger reductions in the proportions of medium vehicles speeding by a margin of 5 km/h or 10 km/h or more. With regard to higher margins (15 or 20 km/h or more), however, the pilot vehicle had larger effects on the light vehicles than on others.

Motorists were less likely to speed when the proportion of large vehicles (medium and heavy) in the traffic stream was greater. These large vehicles are generally slower than the light vehicles in accelerating from a stop position or a slow speed. Thus, the vehicles travelling behind these large ones had no option other than to follow the speeds of the large vehicles. Furthermore, results showed that the medium vehicles were less likely to speed compared to light vehicles (the result was non-significant though for heavy vehicles). Thus, both the lower likelihood of speeding and the slow acceleration of large vehicles might prevent light vehicles from speeding when there are higher proportions of large vehicles in a traffic stream.

Motorists were also more likely to speed when workers were not present in work zone. Generally, work was not conducted during the night-time hours. Pilot vehicle operation was also dependent on the presence of workers on road. Results showed that the night-time hours were associated with less speeding than the daytime hours, while absence of the pilot vehicle was associated with more speeding. This apparent contradiction warrants further investigation of the effects of pilot vehicle operation on responses to the presence of workers.

Although presence of the pilot vehicle influenced motorists’ speeds in the work area considerably, no significant halo effects were found at a location 560 meters downstream of the work area. The comparison of average speeds during daytime hours when the pilot vehicle was present with when it was not revealed no significant differences. However, the average speeds during night-time hours were higher than those of the daytime hours, although this difference may not necessarily relate directly to the status of the pilot vehicle. It is possible that speeds at night are generally higher than during the day. A comparison of the average speeds on nights following a day with pilot-car operation with those following a day without pilot vehicle operation revealed no significant difference (the average speed was only 0.52 km/h higher in the nights following a day without pilot vehicle operation). Although the average speeds during daytime hours were unchanged, presence of the pilot vehicle was associated with a reduction in the proportion of vehicles speeding by a margin of 5 km/h or more above the posted limit. Reductions in the proportions of vehicles speeding with a greater margin were generally higher for heavy vehicles than for other types of vehicles. This may imply that motorists, especially the heavy vehicle drivers who travel at speeds significantly higher than the posted limit, are more influenced by presence of a pilot vehicle at an upstream location than those who travel at speeds close to the posted limit.

It would be interesting to compare the effects of a pilot vehicle obtained in this study with those of other speed reduction measures. Unfortunately, many of the other measures have been studied in work zones with much higher speed limits (mostly 89 to 113 km/h). The 5.9 km/h mean speed reduction observed with the pilot vehicle is similar to the 7.4 km/h speed reduction (under a speed limit of 105 km/h) and 5.8 km/h reduction (under a limit of 89 km/h) found for EFTCD by Bai and Li (2011). A pilot vehicle appears to have a greater effect on speeds than portable rumble strips or VMS without feedback in Fontaine et al., (2000). However, the speed reductions associated with pilot vehicle operation were less than that reported for a speed feedback system (up to 16 km/h on two-lane roads with 113 km/h posted speed limit by Fontaine et al. (2000) or a speed camera (6.7-12.5 km/h reported by Hajbabaie et al. (2009)) or police presence (17 km/h reported by Huebschman et al. (2003)).

This study examined the effects of pilot vehicle operation on speeds of public vehicles in a long-term large rural highway work zone, which had two lanes with only one open to traffic, in the State of Queensland, Australia. Since the study has not been repeated and the findings have not been validated in other similar work zones because of resource constraints, the results might be subject to various unknown work-zone-specific effects. Furthermore, whether the effects of a pilot vehicle will be similar in short-term or urban work zones has not been tested. Thus, care should be taken in generalizing the results to smaller and short-term work zones, as well as to other parts of Australia and the world with different environmental and regulatory conditions. Further research should include generalizing the results by examining effectiveness of pilot vehicle operation in multiple work zones and how its effectiveness varies with different geometric, traffic, and operational characteristics of work zones. Another important extension of this research would be examining the effects of pilot vehicle operation on the queue and gap characteristics of public vehicles and whether pilot vehicle operation influences the speed variability and the risk of rear-end crashes at the tail of traffic queues, which is a common type of work zone incident in Queensland (Debnath et al., 2013).

CONCLUSIONS

This paper evaluated the effectiveness of pilot vehicle operation in reducing travel speeds in a long-term highway work zone. The analyses revealed that average travel speeds under pilot vehicle operation reduced in the area where the pilot vehicle operated, but not at a location downstream of this area. Even with the pilot vehicle, the mean speed at the work area remained about 6 km/h higher than the posted limit. Speeding by the pilot vehicle may have contributed to this finding. In addition to the effect on mean speed, the presence of the pilot vehicle also reduced the proportion of speeding vehicles. Similar reductions in mean speeds are observed for all types of vehicles; however, the reductions in proportions of speeding vehicles were not similar. The effect of pilot vehicle operation in reducing the proportion of speeding vehicles by a small margin (less than 15 km/h above the limit) was greater for medium vehicles than for other types of vehicles. However, for a larger margin (15 km/h or more) above the limit, the greatest effect is seen for light vehicles. A public vehicle is more likely to speed during daytime hours when the posted limit is 40 km/h and traffic volume is higher than in night-time hours. Higher likelihood of speeding is also associated with higher gaps between vehicles. The pilot vehicle seemed to have greater effect in reducing speeds of the vehicles following it closely in a traffic stream than those which are far behind the traffic stream. Higher proportions of medium and heavy vehicles in a traffic stream were associated with a lower likelihood of speeding. The greater likelihood of motorists speeding when workers are not present in work zone deserves further investigation. Given that the pilot vehicle was non-compliant with the posted speed limit on about one-third of its trips, including an item in pre-work checklists would be beneficial to remind pilot vehicle drivers to keep their speeds within posted limits. When following a speeding pilot vehicle, motorists might be encouraged to speed both when a pilot vehicle is in operation and when it is not. Therefore, improving compliance of pilot vehicle has potential to help better improve compliance of all motorists.

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