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Review of the literature on daytime running lights (DRL)

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Review of the literature on daytime running lights (DRL)

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Abstract

This review of the research on daytime running lights (DRL) was conducted to provide input to an examination by the Department of Transport and Regional Services of the suitability of DRL for Australian conditions. The INROADS, TRIS and ITRD data bases and the internet were scanned, and telephone consultations were held with key officers in the road and transport authorities of the different Australian jurisdictions. There is a substantial body of evidence which shows that DRL are effective in reducing daytime crashes, but studies disagree as to the size of the reduction. It is therefore difficult to predict what impact they might have in Australia. The best technical option for DRL appears to be dedicated DRL with an intensity of 1200 candelas, designed to direct its light towards oncoming vehicles, and with reduced power requirements. Dipped headlights direct most of their light at the road surface and have higher power requirements. Dedicated DRL have favourable benefit-cost ratios, while full-time operation of dipped headlights has a benefit-cost ratio close to one. The costs of providing DRL would be considerably reduced if the DRL operated only in conditions of low ambient lighting. Although visibility experiments suggest these are the only conditions under which DRL are of benefit, there are no studies available which relate crash reductions to ambient light conditions, so that it is not clear how much of the benefits associated with full time operation would be realised. In view of the jurisdictions' preference for full-time operation, evidence in support of this option would have to be persuasive before it was adopted. An appropriate course of action for Australia will be to await the outcome of the determinations currently taking place in Europe in relation to DRL, and which are expected to be complete by the end of the year. At that stage it would be appropriate to give the issue full consideration in the light of the European decision.

Keywords

Daytime running lights, DRL, Conspicuity, Cost-benefit

Notes

(1) ATSB reports are disseminated in the interest of information exchange.
(2) The views expressed are those of the author(s) and do not necessarily represent those of the Commonwealth Government.

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1. Executive summary

1.1 Background

Overseas evaluations have concluded that automatic daytime running lights (DRL) are effective in reducing multiple-party crashes, but many of these studies have been criticised on methodological grounds. Nonetheless, the substantial body of evidence suggesting that there are safety benefits associated with the use of DRL has prompted various proposals for Australia to adopt some form of broad-based DRL requirement, typically by amendment to design rules for new vehicles.

As input to the Department of Transport and Regional Services' examination of DRL, the Australian Transport Safety Bureau (ATSB) has commissioned ARRB Transport Research Ltd to conduct a comprehensive review and analysis of the research literature on DRL.

1.2 Principles

Failure to see another vehicle has been shown by many studies to contribute to a considerable proportion of collisions (Cairney, 1991). DRL are designed to increase the contrast between the brightness of the DRL equipped vehicle and brightness of the vehicle's background. By increasing the visual contrast of a vehicle DRL should, theoretically, allow other road users to see a vehicle more readily than would otherwise be the case, allowing them to respond to the presence of the vehicle sooner in order to avoid a collision.

1.3 Objectives

This project has three primary objectives:

1. To identify and critically review evaluation studies and other relevant research on the impacts of DRL.

2. To discuss the findings in relation to proposals for an Australian DRL requirement.

3. To identify additional research or information required to fully assess the impacts of an Australian DRL requirement.

1.4 Method

In order to identify available evaluation studies and other relevant research on the impacts of DRL, several databases and the internet were utilised. Local, interstate and overseas contacts were consulted in an effort to identify any relevant unpublished material.

Three main bodies of literature were considered:

1. Experimental studies of the conspicuity of DRL in relation to ambient lighting conditions.

2. Studies of crash reductions following the introduction of DRL in other jurisdictions.

3. Literature pertaining to the costs of providing DRL.

Consultations with Australian jurisdictions in relation to unpublished research were extended to the views each contact had on DRL.

1.5 Impact of DRL on visibility

Studies have been conducted on the effects of DRL on visibility distance, speed and gap acceptance, vehicle detection and recognition, and discomfort glare. These studies suggest that DRL increase the probability that a vehicle will be detected when ambient lighting levels are low. They also show that if the DRL are too bright, then discomfort glare and disability glare will result. DRL should be bright enough to ensure performance is better than without DRL, but not so bright as to cause glare.

Only luminous intensities lying within a very narrow range would satisfy this condition. It might be beneficial to have DRL which are capable of varying intensities that alter in response to ambient illumination level.

1.6 Crash reduction studies: cars

Early research has provided a mix of results. Comprehensive reviews incorporating meta-analysis by Elvik (1996) and Koornstra et al. (1979) have systematised these results. Elvik showed that studies of DRL in vehicle fleets provided larger and more consistent effects than studies of traffic systems, and that outcomes are sensitive to the type of measures used. Koornstra et al. carried this analysis a step further by statistically excluding factors such as number of vehicles already using DRL at the start of a trial to estimate the *intrinsic* effects of DRL, ie the effects which would occur when use rate is increased from zero to 100% of vehicles. The effect of this re-analysis was to make many studies which were previously non-significant significant, and show that by far the majority of studies found a reduction in multiple-party daytime crashes associated with DRL. Koornstra et al. proposed a set of relationships relating the extent of crash reductions with DRL to latitude, based on the longer hours of twilight in the higher latitudes. It should be noted that many later studies do not fit this model well.

Studies that have been conducted since the reports of Elvik (1996) and Koorsntra et al. (1997) have generally confirmed the reduction in crash rates associated with DRL, although the size of the reduction varies. Tofflemire and Whitehead (1997) compared crash rates in the same year for Canadian cars with and without DRL, eliminating factors such as weather, economic climate, and enforcement as a possible source of differences. They found an overall reduction of 5.3%, principally due to a reduction in crashes involving vehicles travelling in opposite directions.

A North America study by the National Highway Traffic Safety Administration (NHTSA, 2000) reinforced the sensitivity of outcomes to analysis methods, but showed an estimated effect of DRL was a reduction of 7% in multiple-party daytime crashes, which was statistically significant. Bergkvist (2001) reports upon a study conducted for General Motors Corporation by an independent consulting firm. The study involved a comparison of the crash rates of specific GM, Volvo, Saab and Volkswagen vehicles before and immediately after DRL became standard equipment on these models. The results suggest a reduction in the incidence of target vehicle-vehicle crashes in excess of 5% and a reduction in vehicle-pedestrian collisions of approximately 9%. Farmer and Williams (2002) compared makes and models which included DRL as a standard feature with the same makes and models purchased before this was the case. The reduction in daytime crashes was 3.2%, which was highly significant. When considered separately, all states but one showed a reduction in crashes for the DRL vehicles. However, only in Texas was the reduction large enough to be statistically significant. Lassarre (2002) reports a trial involving a campaign to encourage voluntary use of headlights during the day. Crash rates in the area where the campaign was run were compared with crash rates in neighbouring areas over the same period, and showed a reduction of 58.7% for fatal crashes and for serious injury crashes on major roads, but no reductions in less serious crashes and no effects on crashes on minor roads.

A study by Poole (1999) is of particular interest as it is the only fleet study carried out in Australia. DRL were fitted to 80 fleet vehicles based in metropolitan Western Australia. The crash records of the DRL equipped vehicles over a ten month period were compared with the crash records of a matched sample of vehicles not fitted with DRL. Results based on a time-to-crash analysis found that DRL fitted vehicles took more than five times longer than non-DRL fitted vehicles to be involved in a vehicle-vehicle daytime crash.

1.7 Crash reduction studies: motorcycles

There are reasons for believing that the case for DRL as a countermeasure for motorcycle crashes is even more compelling than that for cars, as cars are more conspicuous than motorcycles. Laboratory studies and field trials have demonstrated that motorcycles equipped with DRL are more easily seen than motorcycles without such equipment.

1.7.1 Studies of causal factors in motorcycle crashes

Studies of causal factors in motorcycle crashes have revealed that crash-involved motorcyclists are less likely to be using DRL at the time of the crash than non-crash involved motorcyclists.

A Californian study on the effects of a law requiring that new motorcycles have DRL fitted revealed no effect on fatalities and a non-significant reduction in vehicle-vehicle daytime crashes. Two studies of the effect of the Australian Design Rule (ADR 19/01) requiring hard-wired DRL on new motorcycles in Australia have been carried out, both finding small but non-significant reductions in crashes. The number of crashes on which these studies were based was too small to conclude that DRL are ineffective.

Two studies from Malaysia and Singapore provide some positive evidence in relation to daytime use of headlights for motorcycles. A national campaign to increase daytime headlight use in Malaysia resulted in an 82% headlight use rate and a reduction in conspicuity-related crashes of 29%. Compulsory headlight use for motorcyclists in Singapore was found to result in a significant reduction in fatal and serious injury crashes.

1.8 Consultations with Australian jurisdictions

Representatives of the traffic authority of each Australian State and Territory were contacted by telephone and asked to comment on each of three DRL options. Representatives from most jurisdictions could offer only personal opinions, but most were in favour of the introduction of DRL in some form. The most favoured of the three options presented is the introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a device that automatically activates either the vehicle's headlights or separate running lights, when the engine is operating. No representatives expressed support for the introduction of State and Territory laws requiring that drivers of all vehicles activate headlights, or separate running lights, at all times of vehicle operation.

1.9 Benefit-cost estimates

Two recent studies of DRL are of particular interest. A New Zealand study considered the costs and benefits of DRL with normal headlight use and with retrofitted DRL. Koornstra et al.'s formulae were used to estimate crash reductions. Special purpose DRL were found not to be cost-effective, while use of normal headlights as DRL was found to be cost effective only when petrol prices were low.

A study carried out for the NRMA and RACV (Paine, 2003) examined technical options for DRL in some detail, and estimated crash savings based on the NSW crash database, using Koornstra's formulae to provide an upper estimate and Berkvist's results as a lower estimate. With the lower estimate, only factory fitted special purpose DRL were found to be cost effective. With higher estimates of crash savings, several options were shown to be cost-effective.

The present study adopted a generally similar approach, based on the VicRoads CrashStats database and Koornstra's formulae. The option of using normal headlights had a benefit-cost ratio of just over 1.0. Costs were greatly reduced by having dedicated DRL which consumed less power. Costs were further reduced by having sensor-activated DRL which only come on in periods of low ambient illumination; in providing a benefit-cost estimate for this option, it was assumed that all crash reductions would be concentrated in these periods, but this assumption is unlikely to be true in practice. Although visibility tests suggest that DRL are effective only in low-light conditions, there do not appear to be any studies that indicate what proportion of DRL-related crash reductions actually occur during such periods.

Differences between these benefit-cost estimates are discussed in detail.

1.10 Unresolved issues

The main issues yet to be resolved are:

- A closer examination of the data on crash reductions in different circumstances to be able to better predict what the effects in Australia might be, although it is unlikely that exact prediction of outcomes in Australia will be possible.
- A closer examination of the costs of providing DRL.
- Consideration of likely road user acceptance.
- The need for arrangements to manage the transition as new DRL equipped vehicles appear on the roads.

1.11 Conclusions

1. There is a substantial body of evidence which shows that DRL reduce daytime crashes. However, there is considerable variation in the size of the reduction reported in different studies.

2. Most studies simply report overall reductions. As a result, three issues remain unresolved, or have little data to support them. Resolution of these issues would clarify the likely effects of DRL in crashes in Australia, or would help decide between having full-time DRL and DRL which operate only under conditions of low illumination. They are:

   - What is the relative effect in built-up areas and open country?

   - How much of the crash savings occurred during the dawn/dusk period, and how much during conditions of low ambient lighting?

   - How have different crash types (cross traffic, right (or left) turn against, head-on, etc) been affected?

3. Empirical work has shown which type of DRL is most suitable. Dipped headlights, even with reduced light output, are not a good choice as much of the light is directed towards the road surface, which is ineffective during daytime (although effective at night). The best option appears to be dedicated DRL with an intensity of 1200 candelas. Although the introduction of an ADR is associated with long lead times, compulsory usage laws have little State support and are associated with compliance and enforcement problems.

4. Opinion in the different jurisdictions around the nation indicates majority support for DRL, although it should be borne in mind that this represents the views of individual officials and not, at this stage, departmental policy. Some of the respondents contacted suggested that a clearer indication of the likely benefits in Australia would be required before full support would be forthcoming. Most favoured a national approach, and some were conscious of the benefits of aligning practice with that in the larger motor vehicle markets. A majority indicated a preference for full-time operation of DRL.

5. The benefit-cost analysis suggested the costs of providing DRL would be considerably reduced if the DRL operated only in conditions of low ambient lighting. However, it is not possible to estimate the extent by which the crash reductions might be reduced under this option (refer Conclusion 2). In view of the jurisdictions' preference for full-time operation, evidence in support of this option would have to be persuasive before it was adopted.

6. An appropriate course of action for Australia will be to await the outcome of the determinations currently taking place in Europe in relation to DRL, and which are expected to be complete by the end of the year. At that stage it would be appropriate to give the issue full consideration in the light of the European decision, and the outcomes of Paine's and the present analysis.

2. Introduction

2.1 Background

Overseas experience over a number of years has suggested that, on balance, daytime running lights (DRL) are effective in reducing multiple-party daylight crashes. While there are methodological problems with a number of studies, the body of evidence favouring DRL is now substantial.

To date, there has been little support in Australia for DRL. Despite the generally positive findings reported in the literature, there has been uncertainty about the potential impacts of DRL under Australian conditions. There are four primary reasons for this uncertainty:

1. The crash reductions associated with DRL in key studies has varied considerably.

2. Most DRL studies have been conducted in countries with higher mean latitudes and longer twilight periods than Australia, prompting some doubts about the relevance of overseas findings. This is reinforced by the generally bright daylight conditions over most of the continent for much of the year.

3. The only substantial Australian experience with DRL relates to motorcycles.

4. There is uncertainty about the cost-effectiveness of compulsory DRL, even when significant safety benefits are assumed.

In response to a request from the Australian Transport Council, the Department of Transport and Regional Services (DOTARS) is proposing to re-examine the case for mandatory DRL in Australia, taking into account the most recent available evidence.

As input to the Department of Transport and Regional Services' examination of DRL, the Australian Transport Safety Bureau (ATSB) has commissioned ARRB Transport Research Ltd to conduct a comprehensive review and analysis of the research literature on DRL.

This review and analysis coincides with work currently being undertaken to allow the European Commission to clarify the best option for the introduction of DRL across the European Union (Jacques Commandeur, researcher at SWOV (Netherlands Traffic Safety Institute), personal communication 20th June 2003). Research institutes from Norway, Finland and the Netherlands are involved in the project, which is expected to report at the end of 2003. The specific objectives of the program are:

1. To assess the effectiveness of the currently legislated requirements for the use of DRL in the EU and elsewhere, and how that legislation has been implemented in these countries.

2. To assess the various evaluations and make recommendations for the introduction of DRL, taking into account the range of possible impacts, environmental as well as safety.

3. To develop possible implementation strategies for DRL in the EU, based on steps (1) and (2), and develop further recommendations for optimising the outcomes associated with the introduction of DRL.

2.2 Principles

Failure to see another vehicle has been shown by many studies to contribute to a considerable proportion of vehicle-pedestrian, vehicle-cyclist, and vehicle-vehicle collisions (e.g., Sabey & Stoughton, 1975, Cairney & Catchpole, 1991). The probability of detecting an object depends on a number of properties, including the contrast of the object against its background, its angular size and its motion (Rumar, 1981).

It is not practical to manipulate an object's size, and there are many situations on the road where there are few cues to movement (eg when the object is moving directly towards the observer). Ensuring a sufficient level of contrast between a vehicle and its background is however feasible, light colour being the simplest way to achieve this. Light colour has limitations, however, particularly during conditions of low ambient illumination when very low levels of light are reflected by the vehicle or the background makes it difficult to notice the vehicle.

The effect of providing a light source on the vehicle is to ensure that there will be a contrast with all backgrounds, even when light levels are low. This increased probability of detection relies on the fundamental properties of the visual system, and will remain an effective aid to visibility in the long term.

Increased contrast between the vehicle and the background against which it is viewed should allow a vehicle to be detected sooner than it otherwise would. In turn, this allows selection of a path or speed which avoids conflict with the other vehicle, or a change of path or speed to prevent a conflicting movement resulting in a collision.

2.3 Overview of previous research

Laws that mandate the use of DRL for cars have been implemented in Finland, Sweden, Norway, Iceland, Canada, Denmark, and Hungary (Bergkvist, 2001). The US has arrangements which permit manufacturers to provide DRL as standard equipment. Many car manufacturers, including General Motors, Volvo and Saab, have offered DRL as standard equipment on some of their models for a number of years now.

Research related to DRL relates to three basic issues:

1. Lighting studies. These involve studies of the daylight conditions under which DRL are likely to be of benefit, and the characteristics of DRL required for effective performance under different circumstances. Most of these studies involve field experiments using real vehicles and lights in off-road environments.

2. Effects of DRL on crash reduction. These are of two types: fleet studies and system-wide studies. In fleet studies, DRL have been introduced to individual vehicle fleets operated by organisations with the aim of improving crash outcomes. In system wide studies, all vehicles have been required to commence operation with DRL, and the impact on overall crash statistics monitored. Both types of study have their own methodological pitfalls.

3. Studies relating to the cost of providing and operating DRL.

Three Australian studies are particularly relevant to the present project:

- Williams (1989) investigated the case for earlier lighting up times in Australia, based on careful analysis of dusk and dawn conditions. Unfortunately, the analysis did not extend to expected crash reductions.

- Second, Poole (1999) reports a fleet study carried out in Perth, Western Australia. Although a small study, it is interesting in that it achieved exceptionally high levels of crash reduction.

- Finally, a report for the NRMA and RACV (Paine, 2003) became available just as the final draft of the present paper was being prepared. This project had a very similar brief to the present report, and comes to similar conclusions. However, it explores in some detail the technical options for DRL and contains no critical discussion of studies reporting crash reductions for DRL. The present paper has the opposite balance, critically reviewing the outcome evaluation studies and their underlying methods, but accepting a very broad and generic model for estimating the costs of DRL. The Paine study and the present one therefore closely complement one another.

2.4 Options under consideration

Four options are considered in the present report. The project brief required indicative benefit-cost analyses of three options:

- The introduction of an Australian Design Rule requiring all new vehicles sold in Australia to be fitted with a device that automatically activates either the vehicle's headlights or separate running lights, when the engine is operating.

- The introduction of an Australian Design Rule requiring all new vehicles sold in Australia to be fitted with a sensor operated device that automatically activates the headlights or separate running lights in conditions of low light.

- The introduction of State and Territory laws requiring drivers of all vehicles to activate headlights, or separate running lights, at all times of vehicle operation.

ARRB TR's proposal suggested a fourth option to be investigated, that of operating headlights under low beam for an additional period before sunset and after sunrise.

2.5 Objectives

This project has three primary objectives:

1. To identify and critically review evaluation studies and other relevant research on the impacts of DRL.

2. To discuss the findings in relation to proposals for an Australian DRL requirement. Issues addressed in the discussion include:

    - The relevance of overseas DRL experience to Australian conditions;

    - The probable effects on multiple-party daylight crashes involving DRL-equipped vehicles, and the potential effects on total number of serious or fatal crashes;

- The likely cost-effectiveness of an ADR requiring all new vehicles to be fitted with automatic DRL (that activate lights whenever the engine is running);
- The likely cost-effectiveness of an ADR requiring all new vehicles to be fitted with sensor operated DRL (that activate lights only in low light conditions); and
- The likely cost-effectiveness of compulsory use laws requiring all drivers to activate lights at all times of vehicle operation.

3. To identify additional research or information required to fully assess the impacts of an Australian DRL requirement.

3. Method

The databases that were searched included the Transport and Road Update (Australian), the Transport Information Service (US), and International Transport Research Documentation (European). Local, interstate and overseas contacts were consulted in an effort to identify any relevant unpublished material.

Three main bodies of work were considered:

1. Experimental studies of the conspicuity of DRL in relation to ambient lighting conditions.

2. Studies of crash reductions following the introduction of DRL in other jurisdictions.

3. Literature pertaining to the costs of providing DRL.

Consultations with Australian jurisdictions in relation to unpublished research were extended to the views each contact had on the DRL options under consideration.

4. Impact of DRL on visibility

4.1 Overview

There is ample evidence that DRL increase the probability of detecting a vehicle under conditions of low ambient illumination, and that the brightness of DRL must exceed a certain threshold for them to be effective. There is also ample evidence that DRL will cause glare problems and mask vulnerable road users such as cyclists and pedestrians if they exceed a certain brightness.

The evidence for these propositions is presented and discussed in Sections 4.2 to 4.6.

4.2 Effect of DRL on visibility distance

Early work on the impact of DRL on distance at which vehicles become visible to an observer involved direct paired comparisons of whether test subjects judged a vehicle with lighting to be more conspicuous than a vehicle alongside it without lighting (Horberg & Rumar, 1975; 1979). During daytime light conditions, a lamp with an output as low as 50 candela resulted in the lit car being judged as more visible than a car without any lights, but better visibility was only clearly apparent when light output reached 400 candela.

More objective judgements have been obtained in experiments which involved the detection of a vehicle with or without additional lights (eg., Attwood, 1975; Kirkpatrick, Baker, & Heasley, 1987; Perel, 1991). These experiments demonstrate that vehicles with DRL can be detected at greater distances than those without. The results of these experiments have limited direct application in real-life driving however, because it is only in exceptional circumstances that being able to detect a vehicle at very long distances has implications for driving decisions. Much more important is the ability to detect vehicles at shorter range, as failure to do so could result in a collision. Studies based on detection at shorter ranges are discussed in section 4.4.

As studies on detection distance have been reviewed in detail by Koornstra et al.(1997), it is not necessary to describe them in detail here. Because different investigators have used different experimental settings, especially in regard to different daylight levels, and because there are differences in experimental methods between studies, there is little consistency amongst investigations as regards to many of the critical values. However, there is consensus regarding the overall pattern of the results. The principal findings of studies on detection distance are:

- Detection distance increases when lights are present, and increases with increasing intensity of the lights.
- Greater luminous intensity is required to increase detection distance as the angle from the observer increases.
- Requiring the observer to carry out another task as the main task, and the detection task as a secondary task, results in an increase in the intensity of the light required to effect an increase in the detection distance (Ziedman, Burger, & Smith, 1990).

4.3 Speed and gap acceptance

It has also been claimed that DRL result in more accurate and therefore safer judgements of speed and distance. Data from Horberg (1977), for example, suggests that vehicles with lights are judged by observers to be closer than vehicles without lights, the size of the effect varying with the intensity of the light.

Attwood (1981) investigated whether lighting influenced 'gap acceptance'. Test subjects were asked to decide whether they could just overtake safely as a car, with or without lights, approached from the opposite direction. At moderately low levels of ambient luminance, the minimum size of the gaps accepted was greater when the car displayed a 600 cd light than when it displayed a 200 cd light or no light. When ambient light fell to very low levels, the gaps had to be far greater before they were accepted as safe with both lamp intensities.

Koornstra et al. (1997) cite two studies (Olsen, Halstead-Nussloch & Sivak, 1979; Radideau, 1979) where drivers waited at an intersection while another vehicle (equipped with additional lights or not) approached, and were asked to say whether there was a sufficient gap to cross in front of the approaching vehicle. The results from both studies were ambiguous. When compared to cars without DRL, higher percentages of shorter gaps were accepted and rejected for cars with DRL (presumably there were fewer cases where the driver was undecided).

No studies of the effect of DRL on judgements of the speed of cars appear to have been carried out, but Koornstra et al. (1997) cite two studies which have investigated the effect of DRL on the perception of motorcycle speed. Unfortunately, they produced contradictory results. Shew, DaPolito, and Winn (1977, as cited in Koornstra et al., 1997) found that speed estimates were higher when headlights were off, implying that DRL will lead to judgements about speed that are less safe. Howells et al. (1980, as cited in Koornstra et al., 1997) found that whether headlights were on or off made no difference to observers' speed estimates.

The evidence that DRL affects judgements of available gaps or speed is therefore equivocal. In practice, the ability to judge speed or distance accurately is likely to have a very minor impact on driver decision making compared to the ability to reliably detect vehicles on conflicting paths. Cairney and Catchpole (1991) carried out a detailed investigation of witness statements relating to crashes and found that failing to see the other party in a crash was very frequent, ranging from 69% to 80% of vehicle-vehicle crashes, according to the type of crash. In contrast, in only 9% of vehicle-vehicle crashes was misjudgement of speed or distance reported by drivers to have been a contributing factor. Possible effects on gap acceptance or speed judgements should therefore be recognised as a less important factor than failure to detect the other vehicle.

4.4 Detection and recognition

From the preceding discussion, it is apparent that detection of the other road user is essential for making appropriate decisions in traffic. It is also important that the driver be able to recognise the type of road user encountered to ensure an appropriate course of action is taken. Cobb (1999) has carried out the most realistic investigation in this regard. He had participants drive in their own cars round a test track where tree plantings were used to simulate building lines. Participants were obliged to concentrate on the driving task as it was an unfamiliar, reasonably demanding environment in which other people were also driving. Target vehicles with DRL of different intensities were used in the experiment. The experiment was carried out over several days, late in the afternoon with falling light levels.

When participants made a right turn at crossroads, they were confronted on their left (on most occasions) by a target vehicle with or without one of the versions of DRL showing, and with a motorcycle or a bicycle present on some trials. On some occasions, there was no vehicle present, which maintained a degree of uncertainty on the part of the subject. A diagram of the experimental setup is presented in Figure 1.

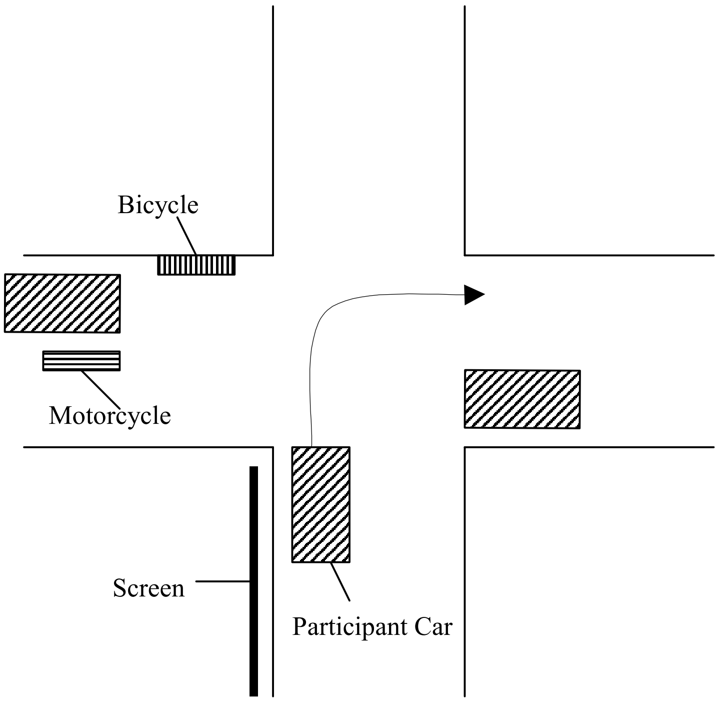

Figure 1: Cobb's experimental condition

The "objective" part of the experiment required the drivers to say as they were making the turn whether or not a car, motorcycle or bicycle was present on the adjacent road while they were making the turn. The "subjective" part of the experiment followed, when the participants had to rate a vehicle waiting for them as they turned the corner, according to how easy it was to see and how dazzling the lights were.

One aspect of Cobb's results are confusing. Light conditions were classified according to whether it was dark (up to 10 lux), dusk (10 to 400 lux), dull (400 to 3000 lux) or bright (over 3000 lux). Light conditions were also classified according to whether they were clear or cloudy, but these categories do not appear to match with the categories based on physical light measurement. The research team's interpretation of this is that there is some overlap between clear or cloudy on the scale based on physical measurements, as might be the case where a period late on a clear day is compared with an earlier period on a day where there is cloud accompanied by diffuse sunlight.

Participants failed to see many of the vehicles in the experiment, missing almost 1% of cars, 8% of motorcycles and 5% of bicycles. All missed vehicles occurred during cloudy conditions; none during clear conditions.

The performance of observers is expressed as “rate multipliers”, which is a score related to the average number of wrong responses. A score of more than one represents higher than average wrong responses, less than one represents fewer than average wrong responses. For driver detection of cars, wrong responses were most frequent in dark conditions, and with no DRL or with the least intense DRL. There was however, no statistically significant interaction between the effects of daylight level and the intensity of the DRL on the test car. This means that the effect of various DRL shown on the test car was the same for all ambient light levels and the relative effect of daylight level is the same for all DRL intensities. For driver detection of motorcycles, below average performance tended to occur only at the highest level of DRL intensity, possibly a result of the DRL masking the presence of the motorcycle. For driver detection of bicycles, performance was below average for all DRL intensities in Dusk and Dark conditions, and for all daylight conditions with the highest intensity DRL.

These findings suggest that under certain conditions, DRL have a considerable masking effect. The data were therefore combined by Cobb to take all vehicle types into account, giving equal weighting to each (see Table 1). These results suggest that DRL with an intensity between 165 candela and 1250 candela will result in better detection performance than average under all light conditions except Dark (see heavily shaded portion of Table 1). Although performance will be worse than average in dark conditions, when the rate multipliers for 165 candela and 1250 candela are compared with no lights under these conditions, performance will still be approximately three times better with the DRL than it would be without them.

Table 1: Combined rate multipliers (adapted from Cobb, 1999)

Daylight Level	Lights Shown on Test Car				
	Zero	**13 cd**	**165 cd**	**1250 cd**	**25 Kcd**
Day	1.04	1.18	0.31	0.34	1.66
Dull	1.35	1.53	0.40	0.44	2.16
Dusk	1.35	1.53	0.40	0.44	2.16
Dark	5.93	6.72	1.76	1.93	9.48

To return to the earlier, confusing point. Although scores with DRL were much better in Day, Dull and Dusk conditions, all the missed responses represented by these cells occurred in cloudy conditions, none in clear conditions. It can therefore be concluded that the differences between the lighting sets are due to differences in performance in cloudy conditions alone, and that DRL improved performance only under cloudy conditions. However, it appears these cloudy conditions extended over the full range of daylight levels determined by physical measurements.

Cobb’s data for the subjective responses follow a much simpler pattern. Judgements of the ease of seeing the target vehicle increase slightly with increasing DRL intensity, with the 165 candela DRL being judged on average, to make the task half-way between ‘sufficient’ and ‘easy’. The ratings for glare increase in a highly uniform manner as DRL intensity increases, with little difference among the daylight conditions. At 165 candela, the ratings over all conditions are tightly clustered around 'noticeable', while at 1250 candela, they are more widely spread but centred on 'acceptable'.

4.5 Discomfort glare

Extensive work not directly related to the DRL issue has been carried out on discomfort glare. However, the findings are relevant to the present discussion.

Kirkpatrick and Marshall (1989) studied the effects of different headlight intensities on discomfort glare when ambient light was approximately 1,900 lux and headlights were viewed in a rear-view mirror. A lamp with an output of 1000 candela was regarded as 'satisfactory', a lamp with an output of 2000 candela was considered to be 'just admissible' by 80% of test subjects, and all lamps with a brightness in excess of 2000 candela were judged as 'disturbing' or 'unacceptable'. An earlier experiment found the 1000 candela lamp to be 'just admissible' rather than 'satisfactory' (Kirkpatrick et al., 1987), but this was attributed to using a more restricted range of lamps in the earlier experiment, the brightest of which was 2000 candela. The tendency of participants to adjust their responses to the range of stimuli to which they are exposed in an experiment is a reliable phenomenon which has been well documented and extensively investigated, for example, in the classical work of Helson (1964).

The Society of Automotive Engineers (SAE) has also carried out extensive work in the area of discomfort glare. A test carried out in Florida found that at an ambient illumination of 90,000 lux (bright daylight), a 600 candela lamp was hardly noticed, a 1500 candela lamp was more noticeable, and a 5,000 candela lamp was even more noticeable but was not considered too bright (CIE, 1990; SAE, 1990). Lamps of greater intensity than 5,000 candela were considered too bright. The 600 candela lamp was more visible when ambient light dropped to 8,000 lux. Further tests in Washington, DC, found that over 20% of assessors found lamps with an output of 2,400 candela to be too bright. During twilight, a lamp with a 1,000 candela output produced a similar response.

4.6 Conclusions regarding effects of DRL on visibility

The available evidence shows that DRL increase the probability that a vehicle will be detected when ambient lighting levels are low. It also shows that if the DRL are too bright, then discomfort glare and disability glare will result. A full understanding of the results involves complex interactions of ambient light levels and DRL intensity. These relations have been elegantly summarised in the ingenious diagram shown as Figure 2, developed by Hagenzieker (1990).

The x-axis in Figure 2 represents the ambient daylight level, and the y-axis represents the intensity of DRL. The area of the diagram in the bottom right hand corner, to the right of the line labelled 'threshold', represents the situation where the DRL are not bright enough to be detected. The line labelled 'threshold' represents the point at which light can just be detected with different ambient light levels. The area to the left of the 'threshold' line represents values at which DRL discrimination and recognition is possible, without discomfort glare. The limit for discomfort glare is represented by a straight line, with luminous intensities greater than the line giving rise to discomfort glare at that ambient illumination level. Beyond discomfort glare, disability glare is experienced (that is, glare sufficiently severe that some vehicles and road users are masked). The last dotted line represents the luminous intensity beyond which the light is regarded as blinding, and other road users are completely masked by the light.

The graph illustrates that a headlight with luminous intensity A will be glaring at low levels of ambient daylight but never falls into the ‘too dim’ area. A headlight with luminous intensity B is shown not to cause glare under any ambient lighting levels, although it does fall into the ‘too dim’ category above a certain ambient lighting level.

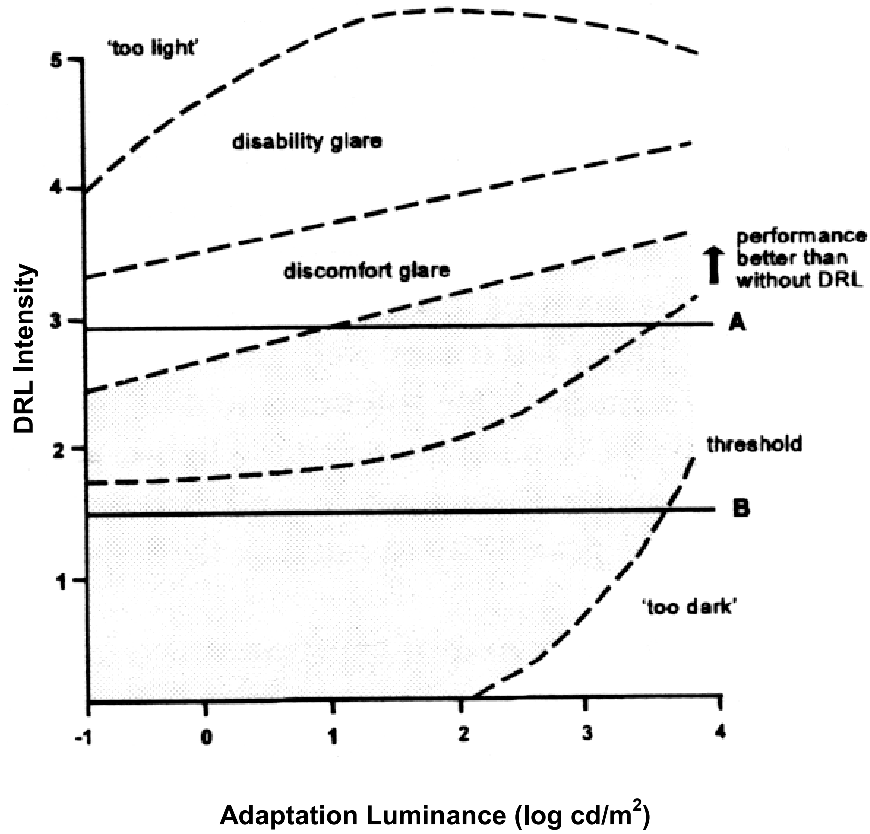

Figure 2. Relationship between visibility benefits, DRL luminous intensity and ambient light levels

The essential task is to ensure the DRL fall within the shaded area. DRL should be bright enough to ensure performance is better than without DRL, but not so bright as to cause discomfort glare. The figure shows that the higher the ambient light level, the greater the brightness of DRL required to effect an improvement in vehicle detection. At the same time, the thresholds for discomfort glare and disability glare also increase with increasing luminous intensity. The diagram indicates that precision is required to select a luminous intensity for DRL that would meet these conflicting requirements under all conditions, and that only luminous intensities lying within a very narrow range would satisfy this condition. Alternatively, it might be better to have DRL which are capable of varying intensities that alter in response to ambient illumination level. DRL of such a design would be less likely to create glare problems at lower levels of illumination, and more likely to have visibility benefits at higher levels of illumination.

5. Crash reduction studies: cars

5.1 Methodological considerations

DRL should affect only multiple-party daytime crashes. Because DRL is a daytime conspicuity aid, night time crashes cannot be affected. Because the effect of DRL is to alert other road users to the presence of the vehicle, single vehicle crashes cannot be affected, except perhaps in some of the exceptional cases where they occur as a result of avoiding another vehicle. Multiple-party daytime crashes have therefore been the focus of most research into DRL.

Studies of the effects of DRL have been of two types, fleet studies and traffic system studies. The former refer to the situation where DRL has been introduced as a countermeasure in a fleet operated by a single organisation, the latter to the situation where DRL have been introduced to the whole traffic system, either by campaigns to encourage their use or through legislative changes requiring that drivers do so. Many of the recent influential studies have been a variation on the fleet study, where particular models have been released on the market with DRL as a standard feature, while other vehicles using the traffic system do not have this feature.

True fleet studies have some methodological problems, in that they may have been introduced as part of a package of measures following an adverse crash history, so the effects of DRL may be confounded with other measures and be subject to regression to the mean effects. Other possible problems are assignment of best (or worst) drivers to the treated vehicles, thus biasing the results. Finally, there is the possibility that drivers are aware they are part of a trial, and so drive more carefully as a result.

System wide studies require care in their design to avoid methodological problems. While many authors acknowledge this need for care in the design, this is frequently overlooked in the published analysis. The main issue here relates to the use of the odds ratio as a means of analysis. Many studies rely on comparing the odds of a multiple-party crash during daytime (ie multiple-party daytime crashes/single party daytime crashes) to the odds of a multiple-party night time crash (ie multiple-party night time crashes/single-party night time crashes). The resultant statistic is known as the odds ratio, and although convenient in many ways it is sensitive to changes in the level of night time crashes for reasons which have nothing to do with DRL, such as changing levels of alcohol enforcement or improved delineation. The interpretation of the odds ratio is problematic unless all crashes other than multiple-party daytime crashes have remained close to the pre-DRL values. Many studies are difficult to interpret because they report only the odds ratios, and not the crash numbers on which they are based.

Elvik (1993) drew the distinction between intrinsic effects and aggregate effects. Intrinsic effects refer to the effect of DRL on the crash risk of each car using them. Aggregate effects, in contrast, are the effects of DRL on the total crash rate for a whole traffic system (often a country) within which a DRL encouraging law or campaign is introduced.

5.2 Basic sources

Much of what is known in relation to crash reduction studies has been consolidated in comprehensive reviews incorporating meta analyses by Elvik (1993) and Koornstra et al. (1997).

Elvik conducted a meta-analysis of 17 studies, conducted in several countries, that have evaluated the impact of the use of DRL. These studies are listed in Table 2. One important feature of Elvik's meta-analysis is his comparison of three measures of the effectiveness of DRL, that is:

- *Effect on crash rate:* Crashes per million kilometres of travel.
- *Effect on simple odds:* Changes in the number of multiple-party daytime crashes (associated with the use of DRL) are compared to changes in the number of all other crash types combined.

$$DRL\ Effect = (MD)/(SD+MN+SN)$$

- *Effect on odds ratio:* The ratio of multiple-party daytime crashes to single party daytime crashes is compared to the ratio of multiple-party night time crashes to single-party night time crashes.

$$DRL\ Effect = (MD/SD)/(MN/SN)$$

Based on his analysis of the results of fleet studies, Elvik reports that the use of DRL results in an *intrinsic* effect of a 10-15% reduction in crashes. Recognising the difficulty presented by the odds ratio method of determining the impact of DRL on crash rates, Elvik reports that the results of studies within which odds ratios, simple odds and crash rates were calculated were "highly consistent". He presents a table which suggests that across three different experimental designs the smallest estimated intrinsic DRL effect is a reduction in crashes of 6%, obtained when simple odds are used as an outcome measure. The greatest reduction reported was of 18%, when crash rate is used as an outcome measure. Reductions estimated when the odds ratio measure was used fell between these two values at a 14% reduction.

According to Elvik (1996), the estimated *aggregate* effect of the introduction of DRL laws on multiple-party daytime crashes was a reduction of 3-12%. Aggregate effects were found to be less robust than intrinsic effects as outcome measures. Elvik points out that the studies from which aggregate effects are derived were primarily non-experimental studies of crash rates before and after the introduction of a law or campaign to promote DRL use. These studies were probably confounded because, as mentioned, any change in crash rates may be attributable to factors other than DRL use.

A second feature of interest in his meta-analysis is Elvik's comparison of size of reduction associated with DRL and the number of observations on which it is based. Obviously, the greater the number of observations on which an effect is based, the more weight it ought to be given as an indication of the true direction and size of the effect. The figure is reproduced as Figure 3. It shows that many studies are based on small numbers of observations, and should not be given too much weight. The diagram also shows that the studies which show no effect or a negative effect are few in number and based on small samples. It also shows that the few studies which are based on large numbers of observations show moderate crash reductions with DRL.

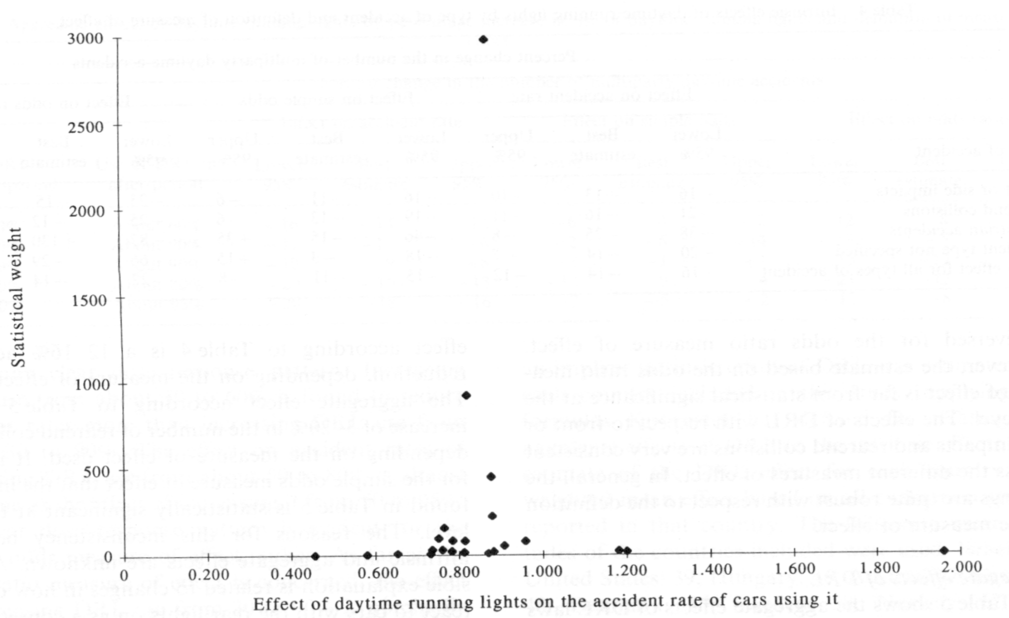

Figure 3: Statistical weight of DRL impact studies plotted against effect size reported (adapted from Elvik, 1996)

Koonstra et al. (1997) took a different approach to achieving comparability between the different studies of DRL effectiveness. By statistically adjusting for the pre-existing level of voluntary daytime light use prior to the introduction of regulations, they were able to approximate the intrinsic effect of DRL, ie what the effect would have been if there had been no use of DRL prior to the trial. Through a statistical process which followed consistent rationale and assumptions, but which was tailored to the requirement of each particular study, they estimated the approximate intrinsic effects of DRL on multiple-party daytime crashes and the associated casualties, although the outcome measures employed by the original authors varied considerably.

Table 2 was compiled from the reports of Koonstra et al. and Elvik (1996) and shows selected results from the original studies and Koornstra et al.'s estimated intrinsic effect of DRL.

The two rightmost columns of Table 2 indicate whether or not the reported results were statistically significant. Statistical significance is a guide to the likelihood that the result obtained occurred by chance, and is related to size of the effect observed, the number of cases on which the comparison is based, and the mathematical assumptions on which the test is based. Greater confidence can be placed in results that are statistically significant.

Table 2 shows some discrepancies between the results estimated by Koornstra et al. and the results reported by the original authors. The studies listed in Table 2 report 23 findings (excluding repeat studies and rear-end crashes), of which four studies show an increase, one no increase and 19 a reduction. Seven of these reductions are statistically significant. Koornstra et al.'s re-analysis changes one of the increases to a reduction, and the no increase to a reduction, and generally tend to increase the magnitude of the reductions. Thirteen of the reductions become statistically significant, and only in one case does a result claimed to be significant by the original authors change to being non-significant.

Table 2: Results of studies included in Elvik's (1996) meta-analysis and of Koornstra et al.'s (1997) re-analysis (continued over page)

Author and Year	Study Type	Country	Results (Original Study)	Results (Koornstra et al.)	Significance	
					Original	Koornstra
Allen & Clark (1964)	Campaign	U.S.	10% reduction in all crashes 25% reduction in all injuries 75% reduction in all fatalities	3% reduction in multiple-party daytime crashes 24% reduction in multiple-party daytime casualties	Not tested	✗
Cantilli (1965)	Fleet	U.S.	44% reduction in multiple-party daytime crashes	44% reduction in multiple-party daytime crashes	✗	✗
Cantilli (1970)	Fleet	U.S.	18% reduction in multiple-party daytime crashes	18% reduction in multiple-party daytime crashes	✗	✗
Andersson, Nilsson, & Salusjarvi (1976)	Law	Finland	11% reduction in daytime vehicle-vehicle casualties 34% reduction in daytime vehicle-pedestrian casualties	60% reduction in casualties in daytime vehicle-vehicle crashes 70% reduction in casualties in daytime vehicle-pedestrian crashes	Not tested Not tested	✔ ✔
Andersson & Nilsson (1981)	Law	Sweden	11% reduction in vehicle-vehicle daytime casualties	60% reduction in vehicle-vehicle daytime crash casualties during winter and 29% during summer	✗ (for whole year)	✗ (Winter) ✔ (Summer)
Attwood (1981)	Fleet	U.S.	45% reduction in all vehicle-vehicle crashes during high visibility times	43% reduction in daytime vehicle-vehicle crashes	Not tested	✔ (but questionable due to assumptions made)
Stein (1985)	Fleet	U.S.	15% fewer daytime vehicle-vehicle crashes	15% fewer daytime vehicle-vehicle crashes	✗	✗

Author and Year	Study Type	Country	Results (Original Study)	Results (Koornstra et al.)	Significance	
					Original	Koornstra
Vaaje (1986)	Law	Norway	14% reduction in daytime vehicle-vehicle crash casualties 17% reduction in daytime vehicle-pedestrian crash casualties	41% reduction in casualties in daytime vehicle-vehicle crashes 53% reduction in casualties in daytime pedestrian-vehicle crashes.	✔ ✔	✔ ✔
Sparks, Neudorf, & Smith (1989)	Fleet	Canada	See Sparks et al. (1993) as that report is based upon same data.			
Hocherman & Hakkert (1990)	Campaign encouraging DRL use in bad weather	Israel	No reduction in daytime vehicle-vehicle crashes	Up to a 32% reduction in vehicle-vehicle crashes in rainy weather	N/A	✗
Elvik (1993)	Law	Norway	2% increase in casualties in daytime vehicle-vehicle crashes 2% increase in pedestrian casualties in daytime vehicle-pedestrian crashes 17% reduction in multiparty daytime casualties during summer 20% *increase* in daytime rear-end collisions	43% reduction in casualties in daytime vehicle-vehicle crashes No decline in pedestrian casualties in daytime vehicle-pedestrian crashes 61% reduction in casualties in multiple-party daytime crashes in Summer	✘ ✘ ✔	✔ ✘ ✔ Not tested
Hansen (1993)	Law	Denmark	See Hansen (1994) same data, longer experimental period.	See Hansen (1994) same data, longer experimental period.		
Kuratorium fur Verkehrssicherheit (1993)	Fleet	Austria	29% reduction in multiple-party daytime casualties	14% reduction in multiple-party daytime casualties	✔	✘

Author and Year	Study Type	Country	Results (Original Study)	Results (Koornstra et al.)	Significance	
					Original	Koornstra
Sparks, Neudorf, Smith, Wapman, & Zador (1993)	Fleet	Canada	28% reduction in DRL relevant multiple-party daytime crashes 22% reduction in DRL relevant multiple-party daytime crashes excluding twilight crashes	27% reduction in DRL relevant multiple-party daytime crashes	✔	Not reported
Arora, Collard, Robbins, Welbourne & White (1994)	Vehicle Standard	Canada	8% reduction in multiple-party daytime crashes	14% reduction in multiple-party daytime crashes	✔	✔
Hansen (1995)	Law	Denmark	7% reduction in vehicle-vehicle daytime casualties	30% reduction in daytime vehicle-vehicle casualties	✔	✔
			4% reduction in daytime vehicle-cyclist casualties	17% reduction in daytime vehicle-cyclist casualties	✘	✔
			16% *increase* in daytime vehicle-pedestrian casualties	16% reduction in daytime vehicle-pedestrian casualties	✘	✔
Hollo (1995)	Law	Hungary	18% reduction in multiple-party daytime crashes	12% reduction in all multiple-party daytime crashes	✘	✔

The intrinsic effects reported by Koornstra et al. were generally more favourable than the aggregate effects reported by the authors of law and campaign impact studies. This is only to be expected as the re-analysis procedure attempts to estimate what the effects of DRL would have been had there been no use of DRL prior to the campaign, and eliminates issues such as the extent of compliance with the law or campaign. Another significant point to emerge from Koornstra et al.'s analyses is the apparent tendency for casualties to be reduced to a greater extent than crashes. Koornstra et al. point out that this is consistent with DRL acting as an alerting device. In some cases, there may not be time to avoid a collision, although impact speed may be reduced enough to prevent reportable injuries.

As well as analysing previous studies, Koornstra et al. combined the results of the reviewed studies to plot DRL effect size against latitude. The relationship is presented in Figure 4 (note that AUS stands for Austria, not Australia). According to Koornstra et al., the relationship between latitude and DRL effect size is attributable to the reduced contrasts and visibility in countries with a lower average sunlight angle. Koornstra et al. report that the relationship between DRL effects and latitude is statistically significant despite the fact that it is based on relatively few studies. Koornstra et al.'s model is referred to at several points in this report.

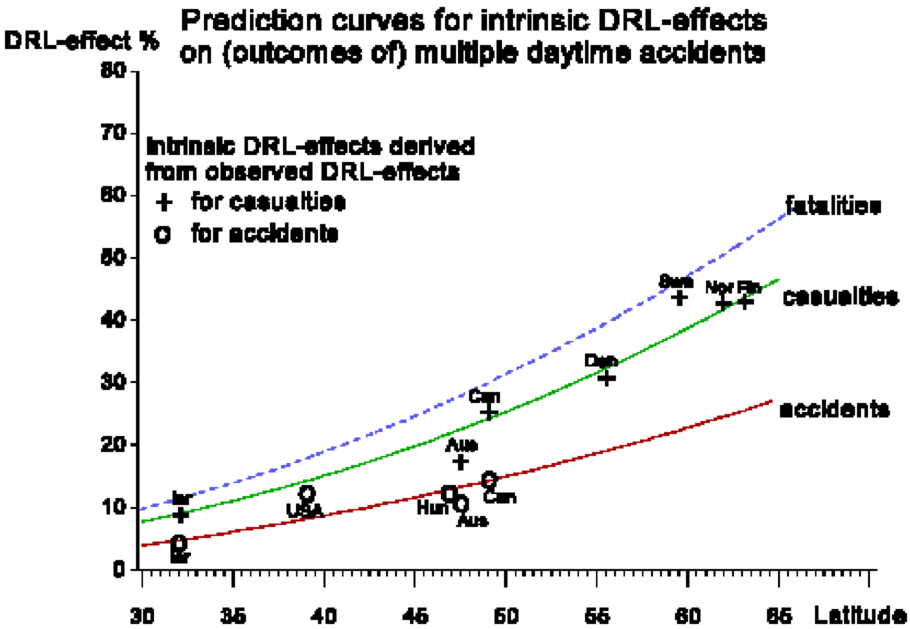

Figure 4. DRL effect and latitude (adapted from Koornstra et al., 1997, p. 4)

5.3 Recent studies

A number of recent studies have appeared since the Koornstra et al. paper. These are reviewed in some detail in this section.

5.3.1 Tofflemire and Whitehead (1997)

Tofflemire and Whitehead (1997) carried out an analysis of the Canadian data, following the same general approach as Arora et al. (1994) but differing in some important particulars. They identified the target crashes (those likely to be effected by DRL) as falling into two crash types, ‘opposing’ and ‘angle’. In the ‘angle’ category, they appear to have included not only cross-traffic crashes, but also any collision involving turning movements, including the ‘left turn against’ category.

Their technique was to select cars registered in 1989 (the last year before DRL had to be fitted to all new cars) and from 1990 (the first year in which new cars had to be fitted with DRL), and compare the number of crashes experienced by each group of 1991. By comparing crash experience of DRL and non-DRL vehicles in the same year, this method eliminated possible confounding factors such as weather, economic conditions and road and traffic conditions. Crash rates per 100,000 vehicles were calculated for each crash type, for each province and nationally. The rates had correction factors applied to make allowance for new cars being driven further than year-old cars, pre-existing DRL being provided by some suppliers in anticipation of the legislation, and voluntary use of lights during the day. The result of these adjustments was an estimate of what the crash rates should have been without the DRL. These rates were compared to the actual results achieved with the DRL, using a Z-test for the difference between proportions applied to the proportions of target crashes experienced by the pre-DRL vehicles and the DRL vehicles.

The result was a statistically significant 5.5% reduction in crashes for the DRL equipped vehicles, primarily the result of a 15% reduction in DRL equipped vehicles involved in opposing collisions. Angle collisions were reduced by only 2.5% (not significant) among DRL fitted vehicles.

This reveals a problem with the categories chosen for the analysis. Consideration of first principles suggests that it is likely that the “left turn against” type of crash would have been reduced considerably since the colliding vehicle approaches head-on, whereas the “cross-traffic” type of event might not benefit nearly as much, because the vehicle approaches at a right angle and may be hidden by features of the landscape. Unlike the night-time situation, a vehicle approaching from the side would not cast a visible pool of light in front of it. It is not possible to say on the basis of Tofflemire and Whitehead’s (1997) analysis whether this difference in DRL effect by angle collision type did occur. If it did, however, the lack of an effect on cross traffic collisions may mask any effect of DRL on ‘left turn against’ crashes.

Tofflemire and Whitehead (1997) found very large differences in overall crash rates among the various provinces. Crash rates for the target categories are more than three times as great for Prince Edward Island as they are for Ontario and Quebec, the provinces with the largest populations. Only in the smaller provinces were significant differences in the rates for ‘opposing’ crashes found. The summary table of the statistical tests results includes an estimate of the statistical power of each of the tests used (the likelihood of detecting a statistical difference, if one exists, related primarily to the number of data items being considered). In all but one case, statistical power was moderate to strong, or strong. There is insufficient data presented in the tables to replicate the tests, which require overall numbers of cases, and numbers or percentage in the target category. The tables presented in the paper contain only rates and percentage differences between rates.

5.3.2 National Highway Traffic Safety Administration (2000)

The authors of the National Highway Traffic Safety Administration report (NHTSA, 2000) adopt a subtly different approach from other studies in that they employ a case-control method. A group of vehicles known to have DRL fitted as standard were selected, along with two comparison groups. The first comparison group was same model vehicles manufactured in years before DRL became standard, and the second was fleet vehicles of the same age as the experimental group but from a manufacturer who did not offer DRL as a standard feature. Daytime vehicle-vehicle crashes and daytime vehicle-pedestrian crashes were identified as the target crash types. Note that this classification includes some crashes which are not likely to be affected by DRL (for example, rear-end crashes), but this apparently is all that was available. Daytime single-party crashes, night-time multiple-party crashes and night-time single-party crashes were all considered comparison crashes.

Crash data for fatal two-vehicle crashes and for vehicle-pedestrian crashes was collected from all 50 U.S. states. To evaluate DRL effectiveness for two-vehicle crashes of all severity levels, data was chosen from States where the databases contained the vehicle identifiers which allowed the appropriate models to be identified. The effect of DRL was estimated using either the odds ratio method commonly used by other investigators, or the simple odds method (see Section 4.2).

The study produced mixed results, which were dependent upon the method used to analyse the data. The odds-ratio method indicated an increase in crashes, while the simple odds ratio indicated a small reduction which was not statistically significant. For non-fatal crashes, the odds-ratio method showed generally positive reductions. When the simple odds method was used, results tended to be more positive. When the two comparison samples were combined, using the simple odds method, the estimated effect was a reduction of 7% which was statistically significant. It is worth noting, however, that the validity of this result has been questioned. Farmer and Williams (2002) suggest that because the estimates combined by the NHTSA were not statistically independent and were based upon different methodologies, the reporting of a 7% reduction in target crashes is not justifiable.

An especially interesting feature of the NHTSA investigation is its inclusion of fatal pedestrian crashes. Daytime single vehicle crashes involving pedestrian deaths were considered to be the target group, and night-time pedestrian deaths, daytime occupant deaths and night-time occupant deaths being considered the comparison groups. Both the odds ratio and simple odds methods were again used. The odds ratio method gave an estimate of 29% effectiveness, but the authors do not say if this is statistically significant. For the simple odds method, the estimated effectiveness was 28% which is statistically significant.

5.3.3 Bergkvist (2001)

Bergkvist (2001) reports upon a study conducted for the General Motors Corporation by an independent consulting firm. The study involved a comparison of the crash rates of specific GM, Volvo, Saab and Volkswagen vehicles before and immediately after DRL (in most cases automatically activated) became standard equipment on these models.

Crash records for the years 1994 to 1997 were drawn from police data from 12 U.S. states and combined with vehicle registration data to determine crash rates per 10,000 vehicle years of exposure. Table 3 shows the relative risk of DRL fitted vehicles when compared with vehicles not fitted with DRL. A ratio less than 1.0 suggests that vehicles with DRL have lower crash rates than those without DRL.

It should be noted that these categories overlap to some extent. Bergkvist reports that all the ratios were significantly different, except for daytime vehicle-vehicle collisions in rural areas.

Table 3: Summary of results of GM study (adapted from Bergkvist, 2001)

Crash Type	Relative Risk
Daytime vehicle-vehicle collisions	0.89
Daytime head-on collisions	0.87
Daytime vehicle-vehicle angle/turning	0.87
Daytime vehicle-vehicle side collisions	0.86
Daytime vehicle-vehicle collisions in cloudy, foggy, rainy days	0.88
Daytime vehicle-vehicle collisions during dusk or dawn	0.91
Daytime vehicle-vehicle collisions in urban areas	0.88
Daytime vehicle-vehicle collisions in rural areas	0.95
Daytime vehicle-pedestrian in urban area	0.88
Night-time vehicle-vehicle collisions	0.95

Bergkvist (2001) goes on to suggest that the difference in night-time vehicle-vehicle collision rates for DRL fitted and non-DRL fitted vehicles may be due to the illumination that DRL provide on vehicles in which the driver has forgotten to use the headlights. There is however, another possible explanation for the consistent difference in crash rates for DRL and non-DRL fitted vehicles. The vehicles which were included in the 'DRL fitted' category were newer than the vehicles that had not been fitted with DRL. Bergkvist does not specify the years of manufacture of the non-DRL group of vehicles. It is possible that DRL were not the only safety feature of the newer models that was not included on the older models. Further, older vehicles are more likely to have risk factors such as tyre wear than are newer vehicles and may also be characterised by different ownership and crash exposure patterns.

Despite the above qualification, it is apparent from Table 3 that the difference in relative risk for DRL and non-DRL fitted vehicles is greater for all the categories of daytime crash than for the night-time crashes. This suggests that reduction in crash risk associated with DRL fitted vehicles is probably not entirely due to the fact that the DRL fitted vehicles are newer.

Overall, Bergkvist's (2001) report suggests that crash rates per year of vehicle exposure are less for DRL fitted vehicles than non-DRL fitted vehicles. Some of the reduction in crash risk for DRL fitted vehicles might be attributable to their being newer than the vehicles that did not have DRL fitted. However, the age of the vehicles sampled does not appear to account for the entire difference in crash rates, which DRL use may well be responsible for. Adjusting for changes in the non-target night-time crashes, the ratios suggest a reduction in the incidence of target vehicle-vehicle crashes in excess of 5% and a reduction in vehicle-pedestrian collisions of approximately 9%.

5.3.4 Farmer and Williams (2002)

Farmer and Williams (2002) made use of the successive introduction of DRL on different models of vehicles for sale in the U.S. at different times. The first group of vehicles they identified was those makes and models which included DRL as a standard feature for the first time in 1995. The same makes and models purchased in 1994 were used as comparisons for this group. The only significant design difference between the two years was the DRL. The second group was those makes and models which first provided DRL as standard in 1996. Vehicles of the same make but from the previous year were used as a comparison for this group. The target models, excluding the comparison groups, made up approximately 4 million vehicles.

Daylight multiple-party crashes (including vehicle-vehicle and vehicle-bicycle crashes) involving the specified categories of vehicles were extracted from nine state crash databases, these states having wide geographic spread. The effects of DRL in each state were estimated by means of the odds ratio (see Section 4.2). A correction was applied to allow for the DRL vehicles being driven more because they are newer.

Odds ratios were combined across the two years to produce an overall odds ratio for each state, and a combined odds ratio to cover the whole sample. When combined across all states, the reduction in daytime crashes was 3.2%, which was highly significant. When considered separately, all states but one had combined odds ratios lower than one (that is, all states but one showed a reduction in crashes for the DRL vehicles). However, in only one state was the reduction large enough to be statistically significant. Interestingly, this state was Texas, the most southerly of the states, where DRL were shown to reduce multiple-party daytime crashes by 5.2%. Texas is located at between 30 to 35 latitude (north). This range is encompassed by Australia. Indeed, Perth, Adelaide, Melbourne, Sydney and Brisbane all fall within 5° latitude (south) of this range. Latitude, among other factors, has some bearing on the light conditions of a region. As already discussed, ambient light conditions play a role in the detectability of DRL and thus can be expected to play a role in the impact of DRL on crash rates.

Farmer and Williams (2002) point out that approximately half of the crashes reported to police are multiple-party daylight crashes, so that the reduction of 3.2% achieved with DRL is equivalent to a 1.6% reduction in overall crash numbers. They note that while this may seem like a small reduction, it comes at small cost.

5.3.5 Lassarre (2002)

Lassarre (2002) reports a recent trial carried out in the Landes *departement* in south-west France. The trial involved a campaign to encourage voluntary use of headlights during the day, effected by widespread distribution of leaflets (including a letter-box drop), signs along the main routes, and media coverage of the campaign. It was evaluated by means of an extensive questionnaire, a wide-ranging survey of headlight use, and an analysis of crashes in the Landes and neighbouring *departements*.

The questionnaire is not immediately relevant to the present discussion, but it is worth noting in passing that direct observation of headlight use indicated considerably lower levels than self-reported use indicated, and that self-reported use was lower among younger people, and this was because they didn't think about it. Interestingly, the possibility of forgetting to switch the lights off at the end of the trip was less of a concern for older people than for younger.

Observation of actual headlight use during daytime revealed that light use varied considerably according to circumstances. Headlight use was most prevalent at dawn and dusk, reaching 88% of vehicles in open country and 81% in built up areas. In rain, use rates were approximately 69% on major routes and 73% on secondary routes in open country, and 30% in built-up areas. In good weather, these percentages reduced to 18%, 24% and 5% respectively. The average rate of light use over all conditions at individual observation sites varied from a high of 43.9% to a low of 4.3%.

To determine the impact of the campaign on crash rates a before and after design with a control group was adopted. The before period was taken as July 1996 to June 1999, and the after period July 1999 to June 2000. Treatment crashes included only vehicle-vehicle crashes occurring in:

- Daylight;
- Good weather; and
- Open country or settlements of less than 5,000 inhabitants.

Two groups of control crashes were considered – similar crashes in five bordering *departements*, and single vehicle crashes in Landes. The crashes in neighbouring *departements* can be considered as controls for weather and seasonal variations, and the single vehicle crashes in Landes as a control for local factors such as increased speed enforcement.

Lassarre dismissed the use of night-time crashes as a control because alcohol plays such a large role in these crashes. The researchers did not attempt any analysis in terms of odds ratios. Crashes were classified according to severity (Injury, Fatal and Serious Injury, and Fatal) and according to road class (All Routes, Main Routes, Secondary Routes). Expected values for 1999-2000 were computed using the 1996-1999 data for the treatment and control sites, and compared with the actual number of crashes which occurred in 1999-2000.

Comparison of the yearly numbers of vehicle-vehicle crashes for Landes shows a fall in all categories of crashes on All Routes and on Major Routes, but an increase in Injury crashes and Fatal and Serious Injury crashes on Secondary Routes. Vehicle-vehicle crashes in the control *departements* increased slightly, apart from the Fatal and Serious Injury category. Single vehicle crashes for Landes increased markedly, and so were unsuitable as controls. They were not considered further in the analysis.

Substantial reductions in crashes were achieved. The biggest reduction was in Fatal crashes, where the reduction was (coincidentally) 58.7% for all Fatal crashes, all Fatal crashes on Major Routes, and all Fatal crashes on Secondary routes. Lassarre reports that the first two of these reductions were statistically significant according to a chi-square test.

The reduction of 40.3% in Fatal and Serious crashes on Major Routes was also statistically significant.

These results are remarkable for a number of reasons, the most obvious of which is the very large reductions achieved. However, it should be remembered that they apply to only non-urban crashes, and only to vehicle-vehicle crashes in good weather. Their impact on overall crashes will be considerably less.

Lassarre does not report any results from the major built-up areas and implies and points out that low levels of light use were achieved in the built-up areas. The impact of DRL use in built-up areas should remain open to enquiry in view of empirical findings from elsewhere. In an experimental setting, Cobb (1999) found that lights greatly increased the probability of seeing the 1% of vehicles that would otherwise be missed in a simulated urban environment. From actual crash data, the recent NHTSA analysis (NHTSA, 2000) found that DRL substantially reduced the incidence of collisions with pedestrians, an essentially urban phenomenon.

5.3.6 Poole (1999)

Poole's (1999) fleet study was the first examination of DRL effectiveness in Australia. Because of the latitude at which Australia is positioned, it tends to have higher ambient light levels and shorter periods of dawn and dusk on average than many of the countries in which other relevant studies have been conducted. As covered in Section 3 of this report, ambient light levels can be expected to influence the effectiveness of DRL in reducing crash rates.

DRL were fitted to 80 white 'Silver Chain Nursing Association' fleet vehicles based in metropolitan Western Australia. Fleet drivers were predominantly females in the low risk age bracket of 30 to 60 years. The vehicles were used by nurses to deliver home based nursing, personal care, home help, and palliative care. These services were generally available from 8 am to 6 pm Monday to Friday, but on an individual basis and for the palliative care were offered outside of these hours.

The crash records of the DRL equipped vehicles over a ten month period were compared with those of a matched sample of vehicles not fitted with DRL. Daytime vehicle-vehicle crashes (excluding rear-end crashes and dawn and dusk crashes) were considered the target crashes.

DRL equipped vehicles were involved in six single vehicle crashes, and one (1.2% of vehicles) vehicle-vehicle daytime crash. The non-DRL fitted fleet vehicles were involved in nineteen single vehicle crashes and eight (10% of vehicles) vehicle-vehicle daytime crashes.

In order to control for road exposure (DRL fitted vehicles travelled further during the study than did non-DRL fitted vehicles) Poole (1999) calculated 'time to crash' results for the DRL equipped and non-DRL equipped vehicles. Poole reports that for DRL equipped vehicles the expected number of kilometres travelled and the expected number of days on road before the car is involved in a conspicuity related crash was more than eight times the exposure expected for a non-DRL fitted vehicle to be involved in a crash. When rear-end crashes were taken into account the expected number of kilometres travelled and the expected number of days on road before the car is involved in a conspicuity related crash was more than five times the exposure expected for a non-DRL fitted vehicle than a DRL fitted vehicle.

Although it seems to offer some very positive results in terms of the effectiveness of DRL on crash rates, the results of Poole's (1999) study must be interpreted with the following methodological issues in mind.

First, Poole's (1999) sample was quite small meaning that the number of crashes upon which the study results are based was small. Indeed, the single vehicle-vehicle daytime crash that was reported for the DRL fitted vehicles occurred when:

> *The driver drove through a 'stop' sign into the path of another vehicle travelling right to left across the intersection. A large vehicle in the right-hand lane, at the time, effectively screened vision to the right. Consequently there was insufficient sight distance available to the driver of the 'colliding' vehicle to avoid a collision (Poole, 1999, p. 12).*

Such a crash is clearly not DRL related, yet had it not occurred the study would have shown that DRL reduces the risk of being involved in a multiple-party daytime crash to 0%. As it was, the reduction revealed translates into an intrinsic effect of 90%. This illustrates the sensitivity of results based on small samples and highlights the need for the results of Poole's study to be considered with this in mind.

Second, Poole (1999) mentions the Hawthorne effect described in Section 4. It is possible that fleet drivers who knew they were supposed to be having less crashes took extra care to ensure that this was the case. Indeed, although exposure adjusted figures cannot be calculated, DRL fitted vehicles were involved in six single vehicle (non conspicuity related) crashes and non-fitted vehicles were involved in 19 single vehicle crashes.

Third, fleet drivers were of a low risk demographic, and the trips made by nurses may not be typical of most trips. Nurses would often have to travel to and from appointments that are emotionally and/or physically taxing. There may well be considerable time pressure and trips may often involve travel on unfamiliar roads. The generalisability of the results of this study to drivers in general must be gauged with these factors in mind.

Figure 5 shows where Poole's study sits in relation to the studies reviewed by Elvik (1996). The statistical weight of each study's results (derived from each study's sample size) is plotted against the size of the intrinsic effect that DRL were found to have. A value of 1.00 on the abscissa is equivalent to no effect. A value of 0.8, around which most results are clustered, is indicative of a 20% reduction in crash rate that has been attributed to DRL use. Poole's study has little statistical weight. This means that the results of Poole's study, because they are based upon a very small sample, may not be as accurate as the results of studies which have greater statistical weight. Indeed, in terms of effect size, the results of Poole's study seem to suggest much larger benefits from DRL than do studies with larger sample sizes.

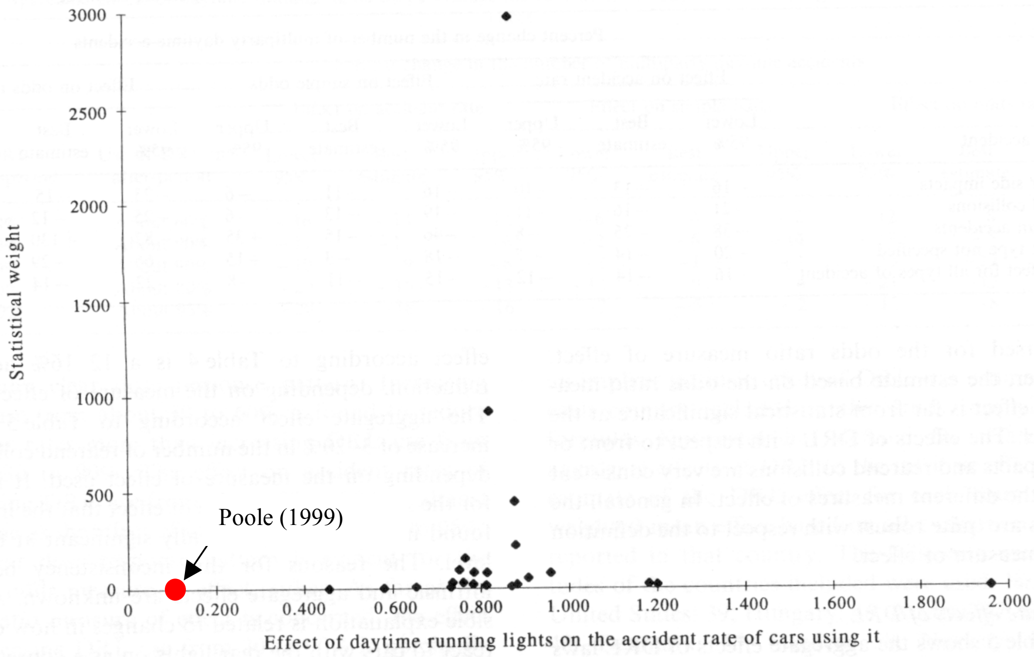

Figure 5: Results of Poole (1999) plotted against results of studies reviewed by Elvik (adapted from Elvik, 1996)

6. Crash reduction studies: motorcycles

Daytime running lights have been proposed as an effective countermeasure for motorcycle crashes for much the same reasons as they have been proposed for vehicles in general. There are reasons for believing that the case for DRL as a countermeasure for motorcycle crashes is even more compelling than that for cars. Cars, are by nature, more conspicuous than motor cycles (Perlot & Prower, 2002). In comparison to cars, motorcycles are smaller, have a more irregular outline, and tend to feature more complex patterns of either predominantly dull or mixed dull, shiny and glazed surfaces. Because of the natural conspicuity of cars, which are wide, have a clean outline and feature an extensive surface of simple pattern, the number of circumstances in which the increased conspicuity offered by DRL will make the difference between a crash and crash avoidance will be less for cars than for a bicycles.

Harrison (2001) has developed the argument that because motorcycles are less frequently encountered than cars, drivers “learn” not to look for them. Over time, drivers come to learn that the probability of encountering a motorcycle in a conflict situation is low, and that that they therefore may not be well-prepared to deal with the situation. In support of this idea, he presents data which shows that the percentage of collisions involving motorcycles is higher for mature drivers than for younger drivers. In theory, DRL are a way of compensating for both low target value and low expectancy as they will almost always provide a strong contrast with the background against which they are viewed.

This prediction would seem to be confirmed by extensive laboratory studies and field trials demonstrating that motorcycles equipped with DRL are more easily seen than motorcycles without such equipment (Dahlstedt, 1986; Janoff, Cassel, Fertner, & Smierciak, 1970; Williams & Hoffmann, 1977). Support for the efficacy of DRL comes from studies (see following Section) which have compared crash involved motorcyclists and randomly selected groups of non crash involved motorcyclists.

6.1 Studies of causal factors in motorcycle crashes

6.1.1 Vaughan, Pettigrew and Lukin (1977)

Vaughan, Pettigrew and Lukin (1977) analysed traffic information forms as completed by NSW Police Officers during a three month period in 1974. Included on the forms was information on whether or not the crash involved motorcycles had their headlights switched on prior to the crash and whether the motorcycle was fitted with a fluorescent “dayglo” headlamp cover – designed to increase conspicuity. Nearly 1500 motorcycle crashes were reported in sufficient detail to allow for inclusion in the analysis. Approximately 402 of these crashes occurred during daylight, involved first impact between a motorcycle and another vehicle, and occurred in the Sydney Metropolitan area (where the observation surveys were conducted).

Control data was collected via field observations conducted in the several locations throughout the Sydney metropolitan area at various times of the day and over all days of the week. For each motorcycle surveyed the presence or absence of headlamp use and “dayglo” cover use was noted.

Although the results reported by Vaughan et al. (1977) include headlamp use and the presence of a “dayglo” cover in the same category, only approximately 1% of motorcycles reported in both the crash data and the observation survey data had these covers fitted. A Chi-square test revealed a highly significant difference in headlamp use between the 1104 motorcycles surveyed and the 402 crash-involved motorcycles. Of crash involved motorcycles only 19% had their headlights switched on just prior to the crash yet 37% of the motorcycles observed during daytime had their headlights activated.

It could be argued that motorcyclists who choose to activate their headlights during the day or to purchase a “dayglo” cover may typically be more safety conscious than those who do not and may also choose to engage in other safety measures that translate into their lower risk of crash involvement. Vaughan et al. (1977) suggest that this is probably not the case, however, and highlight two things to support their argument. First, when analysed separately from other crash types, crashes caused by another vehicle pulling onto the wrong side of the road and by another vehicle pulling in front of a motorcycle to complete a right turn the same pattern (although less pronounced) was revealed. Twenty two percent of crash involved motorcycles had activated headlights and 37% of surveyed motorcycles had activated headlights. Second, there was no significant difference in headlight use between motorcycles involved in single motorcycle crashes (where, presumably in most cases the motorcyclist was responsible) and motorcycles involved in vehicle-motorcycle crashes (two thirds of which are generally deemed to be the fault of the vehicle driver, Henderson, 1970; Hurt, Oullet & Thom, 1981; Messiter, 1972).

6.1.2 Hurt, Oullet, and Thom (1981)

Hurt et al. (1981) investigated 900 motorcycle crashes and 3600 crash reports from the Los Angeles area. The report contains comprehensive crash and exposure data and includes some observations about crash and injury causation. In relation to the DRL the following findings are reported.

- Approximately 75% of motorcycle crashes involved collision with another vehicle, usually a passenger car.
- The failure of motorists to detect and recognise motorcycles in traffic is the predominating cause of motorcycle crashes.
- Crash involvement is reduced by the use of motorcycle headlamps in the daytime.

6.2 Effect of DRL laws on motorcycle crashes

6.2.1 Muller (1982)

Many US states have had laws requiring that motorcyclists use their headlights during daytime for several years now, and since 1972 California has had a law requiring that new motorcycles have headlights which switch on automatically when the engine is started. Effective compliance with the law was delayed until 1978. Muller (1982) studied the effects of increasing headlight use before and after the introduction of the Californian law. For each year from 1976 to 1981, the odds ratio for fatalities was calculated. This time series was then analysed using log-linear analysis. No significant trend was found, suggesting that the laws had had no effect. Similar effects were found for the group of 14 other US states that had headlight use laws for the period 1975 to 1981. There was however, a reduction in the odds ratio in the last two years of the series. This suggests a reduction in vehicle-vehicle daytime crashes, although the results are not statistically significant. This lack of a statistically significant reduction in daytime crashes was interpreted by Muller (1982) to mean that the laws were either ineffective or of minor effectiveness.

Headlight use amongst crash involved motorcyclists was estimated to have increased from 31% to 63-74% over the period. The discrepancy between the findings of the study and those of Vaughan et al. (1977) and Hurt et al. (1981) was ascribed to selection bias mentioned previously. Motorcyclists who choose to use their headlights may be more likely to engage in other safety-related behaviours as well.

6.2.2 Australia

Two studies of the effect of the Australian Design Rule (ADR 19/01) requiring the hard-wired DRL on new motorcycles in Australia were carried out.

6.2.2.1. Rosman and Ryan (1996)

Rosman and Ryan (1996) studied daytime crashes in Western Australia which were related to motorcycle conspicuity over the period 1989-1994. ADR 19/01 came into effect in 1992, with all new motorcycles from that time on being equipped with headlights which operated whenever the motorcycle was in use. The following crash types were included as target collisions:

- Head on;
- Direct right angle;
- Indirect right angle; and
- Side Swipe opposite direction.

There was a small reduction in daytime target collisions between cars and motorcycles compared to similar collisions between cars, but this was not statistically significant. The authors point out that such an effect would be difficult to detect statistically due to the relatively small numbers of new motorcycles being put on the road over the study period, and a substantial increase in the voluntary use of headlights during the day on the part of motorcyclists.

6.2.2.2. Attewell (1996)

Attewell (1996) carried out a similar analysis using NSW data on motorcycle crashes from the FORS Serious Injury Database and the Australian Road Fatality Database for the years 1992 to 1995. Attewell (1996) did not differentiate between conspicuity-related crashes and others, and simply compared numbers of vehicle-motorcycle and single motorcycle crashes which resulted in death or injury for motorcycles that pre- or post- dated the introduction of ADR 19/01. Rear end and motorcycle-pedestrian crashes were excluded.

There was a reduction of 2% in the percentage of vehicle-motorcycle crashes for all crash severities, suggesting that the ADR was having some effect. The effect was greatest for fatal crashes, but this is based on very small numbers, with only 16 fatal crashes involving post-ADR machines. None of the differences were statistically significant. Attewell (1996) reports that the power of the tests used to determine statistical significance was sufficient to have detected any reductions in crash rates in excess of 8%. Larger numbers of crashes would have been required to detect a difference as small as 2%. Despite the fact that none of the changes in crash rate were statistically significant, the direction of effects was consistent for all levels of crash severity.

Like Rosman and Ryan, Attewell (1996) suggests that the absence of a reduction of the magnitude that would have been statistically significant may have been because up to 60% of motorcyclists opted to turn their headlights on during the day even before the ADR was introduced (Harrison, 1988; Johansen, 1987).

6.2.3 Malaysia and Singapore

Two studies from Malaysia and Singapore provide some positive evidence in relation to daytime use of headlights for motorcycles.

6.2.3.1. Radin, Mackay, and Hills (1996)

Radin, Mackay and Hills (1996) report a detailed analysis of conspicuity-related motorcycle crashes following a national campaign to increase daytime headlight use in Malaysia. The campaign consisted of a three month safety campaign, followed by the introduction of a regulation requiring motorcyclists to use their headlights during daytime. The study was carried out in two pilot areas. Before the start of the campaign, virtually no motorcyclists used their headlights in daytime. The campaign resulted in an 82% use rate, which was maintained over the study period, which commenced in January 1991 and concluded in December 1993. The campaign to encourage headlight use began in July 1992 and the regulation came into force in September 1992. Analysis was complicated by the introduction of a new police crash recording form, which was expected to improve the system and result in more crashes being recorded, by the Muslim fasting period, and by more general community holiday periods which were associated with marked changes in travel patterns.

The model which best predicted the conspicuity related crashes was a Poisson model, in which factors to represent the week of the study (to allow for traffic growth over the study period), changes in the recording system, the fasting system, and headlight use were all statistically significant predictors. The estimated effect of daytime headlight use was to reduce conspicuity-related crashes by 29%. Note that this technique relies solely on the changes in the number of daytime conspicuity-related crashes, and avoids the uncertainties associated with odds ratio analyses.

6.2.3.2. Yuan (2000)

Yuan (2000) examined the effects of compulsory headlight use for motorcyclists in Singapore, which commenced in November 1995. All multiple-party crashes involving motorcycles, including motorcycle-pedestrian crashes, for the years 1992 to 1996 were included in the analysis. For the pre- and post-implementation periods, the number of daytime crashes was divided by the number of night-time crashes to estimate the odds of daytime crashes. The pre- odds were divided by the post- odds to provide the odds ratio, and the standard error and confidence interval associated with each ratio was estimated. Under the null hypothesis, the odds ratio = 1, and the significance of the results was tested by determining whether or not the value 1 was within the confidence intervals.

When all crashes were considered, there was no significant effect. When crashes of different severities were considered separately there was a significant effect for fatal crashes and for serious injury crashes but not for minor crashes. Yuan (2000) suggests that the greater drop in serious and fatal crashes compared to minor crashes is due to the role of daytime headlights in alerting people that a collision is about to occur and allowing them to brake for longer and reduce the impact speeds. An effect of this nature was noted previously in relation to the tendency for casualties associated with multiple-party daytime crashes to be more greatly reduced by the use of DRL than the overall crash rates.

Detailed inspection of Yuan's (2000) data shows that it is a good illustration of some of the points raised about the odds ratio methods in Section 4. We can be confident that the reduction in fatal crashes is a real effect, as they fell from an annual average of approximately 40 in the pre- period to only 24 in the year following the introduction of the law. However, it is difficult to be certain about the status of the reduction in serious injury crashes, as they increased from a pre-law average of 91 to 97 in the post-law year. The only reason the odds ratio indicated a reduction in serious injury crashes attributable to the DRL law was that night-time crashes increased by about 50% in the post period, from an average of approximately 72 per year to 109. To what extent this reflects growth in traffic, fluctuations in traffic activity at night, or an increase in night-time crash rates for other reasons is unknown.

There remain some questions about how applicable these studies would be in Australia. In Australia approximately 3% of registered vehicles are motorcycles (Australian Bureau of Statistics, 2001). The Malaysian situation studied by Radin et al.(1996) is very unlike the Australian scene because 60% of vehicles in that country are motorcycles. Singapore is more like Australian cities, but even there motorcycles are 20% of registered vehicles. In both cases, pedestrian-motorcyclist collisions are likely to constitute a substantial proportion of the total but this type of collision is infrequent in Australia. It would be of considerable interest to know what proportion of the crashes in these studies were pedestrian crashes and, for the Malaysian study, to know the proportions of urban and rural crashes and whether they were differently affected.

It should be noticed that in the Malaysian study, the daytime headlight use went from close to zero to over 80%. The effect would therefore appear to be close to the maximum possible. It should also be noted that both these studies were carried out close to the equator. According to Koornstra et al. (1997), who plotted empirically identified DRL effects against the latitude of study locations, the impact of DRL on crash rates so close to the equator would be very small. It would seem that factors other than latitude (perhaps weather patterns and landscape) can play a considerable role in determining the impact that DRL use will have on crash rates.

7. Consultation with Australian jurisdictions

As mentioned in Section 1.4 three design options have been put forward for consideration in this review. These are:

- The introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a device that automatically activates either the vehicle's headlights or separate running lights, when the engine is operating.

- The introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a sensor operated device that automatically activates the headlights or separate running lights in conditions of low light.

- The introduction of State and Territory laws requiring drivers of all vehicles to activate headlights, or separate running lights, at all times of vehicle operation.

Representatives of the traffic authority of each Australian State and Territory were contacted by telephone and asked to comment on each of the DRL options described above. Representatives from most jurisdictions were very careful to point out that they could offer only personal opinions, and in some cases, the opinions of one or two other road authority staff. Table 4 summarises the responses obtained from each road authority contacted.

The contributions of Greg Rowe, Ross MacArthur (Vic), Jim Langford (TAS), Chris Coxon (SA), Mark King (QLD), Steve Jiggins (ACT), Jon Gibson (WA), Pam Palmer (NT) and Phil Sochon (NSW) as reported in this section of the report are gratefully acknowledged.

Most representatives contacted were in favour of the introduction of DRL in some form. The most favoured of the three options considered in this review is the introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a device that automatically activates either the vehicle's headlights or separate running lights, when the engine is operating. Although NSW favoured sensor operated DRL and the TAS representative indicated that both ADR options had advantages, QLD, SA, VIC and WA all expressed a preference for DRL that operate whenever the engine is running. The ACT and NT were less supportive of the introduction of an ADR until further and more conclusive evidence can be presented to suggest that substantial benefits will result.

No jurisdictional representatives expressed support for the introduction of State and Territory laws requiring drivers of all vehicles to activate headlights, or separate running lights, at all times of vehicle operation. The belief that this option would be hard to sell to the community (QLD), difficult to enforce (NSW), and potentially cause many drivers to accidentally run their vehicle battery flat by leaving the lights on while the car is parked (SA) were mentioned as reasons for this. The NSW representative also suggested that evaluating the effectiveness of this particular option would be difficult.

Table 4: Australian jurisdictions' responses to proposed DRL options (continued over page)

Jurisdiction	Preferred option	Comments
VIC (VicRoads)	The most favoured option is the introduction of an ADR requiring DRL to be activated whenever the engine is on. The other ADR may use less energy but we still prefer the first option.	The DRL should be at least as powerful as low beam headlights, anything less will not be enough.
ACT (Department of Urban Services)	No comment.	The crucial issue is whether there is a demonstrated benefit arising from the introduction of DRL. Introducing an ADR would require a detailed regulatory impact statement that would likely need to demonstrate an overwhelming benefit for the ADR option to be considered further.
QLD (Queensland Transport)	An ADR requiring fitting of DRL that activate when the engine is operating would probably offer the best safety benefit. A consistent national approach with progressive introduction of factory fitting to the vehicle fleet would be the most favoured option. The effectiveness and public acceptability of an ADR requiring new vehicles to be fitted with sensor operated DRL would rely on the reliability of the sensor and the accuracy with which it could detect low light conditions experienced by road users (at some distance from the vehicle) using a sensor mounted on the vehicle. Given the variability in contrast detection (especially with age), setting a level at which the sensors would activate the DRL would also be problematic. The introduction of State and Territory laws is not desirable by itself, as national consistency would be difficult to achieve and the benefits of an ADR requirement would be missed. This option would also be the most difficult to sell to the community. Some version of the proposed law could be considered together with an ADR. In effect this would require retrofitting of DRL to some or all of the vehicle fleet or the use of headlights. This would be similar to the situation when seat belts were introduced as a requirement for new cars, and retrofitting was progressively mandated for older vehicles. The existence of an ADR for new vehicles would provide greater credibility for retrofitting, thus addressing the problem of community acceptance.	A literature review with a recommendation to introduce DRL was conducted (Lawson-Baker, 1995) and at that time, Queensland Transport recommended to the ATC that DRL should be introduced. This occurred at the same time as the requirement for motorcycle headlights was rescinded however, so that it was considered that a DRL recommendation would be unacceptable at federal level. Queensland Transport has continued to monitor the relevant research, and is aware of more supporting data from Europe recently. There is support at officer level within Queensland Transport but the department does not have an official stance at this stage, and has not raised the issue with the Minister.

Jurisdiction	Preferred option	Comments
TAS (Department of Infrastructure Energy and Resources)	Generally, State and Territory laws are unlikely to work. An ADR requiring that all vehicles be fitted with automatically activated DRL would probably be the most effective in saving lives but have a less favourable benefit-cost ratio than an ADR requiring the fitting of sensor operated DRL.	Opinions expressed are only personal opinions from the delegated authority rather than overall opinion for the jurisdiction.
SA (Transport South Australia)	TSA would probably support the introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a device that automatically activates DRL when the engine is operating. The jurisdiction would probably oppose the introduction of an ADR requiring vehicles to be fitted with sensor operated DRL and the introduction of State and Territory laws making DRL use mandatory. Transport South Australia would support automatic DRL as any other system would likely have poor driver support. If DRL operation is not an automatic system, then drivers will leave the lights on when they leave the vehicle parked in daylight, with the potential result of a flat battery and considerable inconvenience following the event. As such, Transport South Australia would oppose such options.	Australia could follow Europe's example and use a manufacturers agreement to fit DRL systems in all vehicles under 4.5 tonnes in a specified timeframe which would be much shorter than it would take to get an ADR introduction date. The usage of DRL on fleet vehicles should be introduced; concerns about fuel consumption are not nearly as relevant as road user safety.
NT (Transport and Infrastructure)	Transport and Infrastructure would probably oppose all options presented in light of current available information. It is understood this issue has been considered in the past and that DRL were found to have negligible safety benefits. Whilst there may be some evidence to support the effectiveness of these measures, we need to be mindful of different conditions on Australian roads in comparison to some other countries. The benefits experienced in other countries may not transfer to Australian conditions. If evidence to support a significant safety benefit resulting from these measures can be demonstrated the Department's support for the proposals may change.	If it could be shown that there was merit in the proposal, ie measurable road safety benefits, the NT Department of Infrastructure, Planning & Environment may support the initiative. The Department does not favour imposing a vehicle standard unique to the Australian market – our market is too small, and this is contrary to recent moves to harmonise with ECE and other international standards. There is currently a move towards restricting the use of lights in conditions of good light – members of the community are voicing opposition to the use of lights unnecessarily. This proposal seems to run counter to this move. The use of daytime running lights is yet another power drain on the vehicle which adds to the environmental impact of motor vehicles, and to maintenance costs in replacing batteries and globes.

Jurisdiction	Preferred option	Comments
NSW (Roads and Traffic Authority)	The most favoured option would be the introduction of an ADR requiring the fitting of sensor operated DRL. If a subsequent evaluation in Australian conditions justifies the case then the introduction of an ADR pertaining to DRL that operate whenever the engine is running would probably be supported. The introduction of State and Territory laws avoids a uniform approach, which will make it hard to measure benefits and difficult to enforce without substantial resource allocation.	The overseas data provides more than adequate evidence to support the implementation of daytime running lights in low light conditions in Australia immediately. It also suggests that significant benefit would accrue from the use of daytime running lights in all light conditions. However before this could be recommended for mandatory adoption it would need to be substantiated, as the majority of evidence is based on lower ambient light conditions than is experienced in most of Australia.
WA (Department of the Premier and Cabinet)	The preference expressed by the Western Australian representative would be for an ADR to be developed. Western Australia would probably support the introduction of an ADR requiring all new vehicles sold in Australia to be fitted with a device that automatically activates either the headlights or separate running lights, when the engine is operating. The jurisdiction is most likely to oppose the introduction of State and Territory laws requiring drivers of all vehicles to activate headlights, or separate running lights, at all times of vehicle operation. Further research is required to determine the road safety benefit and the cost benefit if an ADR was to be introduced. As the research to date is inconclusive regarding the benefits of daytime running lights, the Western Australian Government is not in a position to pass State legislation to mandate the use of DRL by drivers or the fitment of such lights to vehicles. However, we will continue to encourage drivers to ensure that they are visible on the roads.	Driving with headlights on to increase motor vehicle visibility is encouraged in WA and WA is interested in finding out whether the introduction of DRL has any proven safety benefit. WA has recently completed a review of vehicle safety features generally. That research looked at the type of vehicle safety features that are available, or are under development, and included a literature review of the likely benefits and costs of these features. The research also examined the availability of safety features for new vehicles, the degree to which manufacturers and motor dealers go to promote these features and the impediments to consumers taking up these safety features. Daytime running lights were included in the review and were listed as a "desirable safety feature" in that they were generally available as standard or optional equipment and are worth considering when purchasing a vehicle. The Royal Automobile Club of WA (RACWA) periodically runs a campaign, *Be Seen Be Safe*, to encourage drivers to keep their lights on during the day. The Road Safety Council's Workplace Road Safety Taskforce is currently examining all safety aspects of company cars and light vehicles, including the issue of daytime running lights. Key stakeholders have developed a company road safety policy to provide a guide for best practice to follow when selecting and maintaining company vehicles.

8. Recent benefit-cost analyses

Two benefit-cost analyses have been conducted recently in Australasia, one for New Zealand's Land Transport Safety Authority (LTSA) and the second for NRMA and RACV. Both reports describe analyses in which crash reduction estimates are based upon the international studies described in this paper. The DRL options considered in each report are different however.

8.1 LTSA (2000)

8.1.1 Sources of information on costs

The costs of two DRL options were considered by the LTSA:

1. The use of existing headlights during the daytime

2. The installation of auxiliary lights on vehicles.

Only running costs were associated with operating existing headlights as DRL. Specifically, these were fuel costs, environmental costs and bulb replacement costs. In addition to running costs, special purpose DRL involve capital costs.

8.1.1.1 Running Costs

Fuel costs were calculated using Lawson's (1986) formulae:

Increase in fuel use per watt of increased electrical load =

$$\frac{\text{Average number of hours taken to drive 100km}}{\text{(watt-hours per litre of gasoline) x (conversion efficiency)}}$$

In New Zealand the average time taken to travel 100 km is 2.71 hours. The heat content of gasoline was taken to be 32 joules per litre and at 277.78 joules per watt, watt hours per litre is 8888.96. Conversion efficiency was taken to be 12.1% based on an engine thermal efficiency of 22% and alternator efficiency of 55%.

The resulting equation was:

$$\frac{2.71}{(8888.96) \text{ x } (0.121)} = .00252$$

By multiplying this figure by the average electrical load placed on a vehicle by its DRL, which will vary according to the type of DRL, additional fuel use per 100 km was calculated. This was then multiplied by the distance travelled by all vehicles during daytime and by the cost of fuel to arrive at total fuel costs.

Environmental costs were calculated using the Land Transport Pricing Study figure of $30.00 per tonne of CO_2 emission, which equated to 9 cents per litre of additional fuel use.

Bulb replacement costs varied depending upon the type of DRL used and were calculated based on manufacturers' product information pertaining to the life of the bulb and the cost of replacing them.

8.1.1.2 Capital Costs

In the LTSA report, auto electricians' quotes for the retrofitting and wiring of DRL (about $100.00 per vehicle) were used as the basis for estimating the installation cost per vehicle. This was then adjusted to an annual cost per vehicle using the assumption that the average life of the vehicle fleet is ten years. No attempt was made to identify the costs that may be associated with installing DRL as standard equipment at the time of manufacture.

8.1.2 Estimation of Benefits

In order to calculate the benefits that might be associated with DRL use in New Zealand, the LTSA used Koornstra et al.'s (1997) formulae to predict the crash reductions that might be expected at the relatively low latitude of New Zealand. Koornstra et al.'s formula is based upon the results of the crash reduction studies described in this paper, which were conducted primarily at higher latitudes than New Zealand. As the LTSA report points out, the Koornstra et al. formulae may not be particularly accurate for estimating DRL effects at low latitudes but is the best available data from which to predict the effect of DRL use in regions where it has not been evaluated previously.

Having calculated expected crash savings the LTSA then applies a "social cost" to each crash, approximately $2.5 million per fatality, $0.5 million per serious injury and $40 thousand per minor injury. The source of these social cost values is not reported.

8.1.3 LTSA Benefit-cost Ratio

8.1.3.1 Existing Headlights

The per vehicle benefit-cost ratio associated with the use of existing headlights as DRL for one year is dependant upon the price of fuel. The LTSA reports that at a fuel price of 80 cents per litre, the ratio is 1.67 in favour of headlight DRL use. At a fuel price of $1.40 per litre however, the ratio is only very slightly in favour of headlight DRL use, at 1.02.

The LTSA also report benefit-cost ratios for greater and smaller crash savings than were estimated using Koornstra et al.'s (1997) formulae. At a fuel price of 80 cents per litre estimated crash savings must be reduced by approximately 50% for the odds ratio to swing in favour of no headlight DRL use (0.83). At $1.40 per litre however, estimated crash savings need only be reduced by 10% before the odds ratio favours no headlight DRL use (0.92).

8.1.3.2 Special Purpose DRL

The benefit-cost ratio associated with the installation of special purpose DRL over a one year period suggests that the per vehicle cost of this option may outweigh the per vehicle benefit, even at a fuel price of 80 cents per litre (0.77). The crash savings estimated using Koornstra et al.'s (1997) formulae would have to increase by approximately 50% before the benefits of this DRL option outweigh the costs.

The LTSA also calculated a 15 year benefit-cost ratio for special purpose DRL, based on the assumption that 15 years constitutes the life of a new vehicle. Although the cost of fitting DRL at the time of vehicle manufacture would be considerably less than the cost of retrofitting, the latter is used by the LTSA in this benefit-cost analysis. Again, the costs of this option were greater than the benefits likely to be associated with it, even at a fuel price of 80 cents per litre. The crash savings estimated using Koornstra et al.'s (1997) formulae would have to increase by approximately 50% before the benefits of this DRL option would outweigh the costs over the lifetime of a vehicle.

8.2 NRMA & RACV (Paine, 2003)

Paine (2003) reports upon a review of DRL that included a benefit-cost analysis.

In his review Paine describes three main types of DRL:

- Low beam headlights;
- Dimmed high beam headlights; and
- Dedicated lights with a defined beam pattern and light intensity.

Paine also mentions LED illuminated rear and side markers as a possible DRL option to be considered as the relevant technology develops.

Each of these DRL options are usually wired so that the DRL illuminate whenever the engine is running.

Paine suggests that low beam headlights are likely to be relatively ineffective in Australia, primarily due to the typically high levels of ambient light. Low beam headlights also waste energy when used as DRL by directing most light at the roadway. They can also produce confusing reflections on wet roads for the same reason. According to Paine, dedicated DRL will offer the best performance under the lighting and road conditions typically encountered in Australia. Sensor operated DRL that become brighter as conditions become brighter are also described as a potentially beneficial option.

8.2.1 Costs

Paine (2003) derives cost estimates for two DRL options and suggests that the costs of other options will lie between the two. For the use of both existing low beam headlights as automatically activated DRL and the use of 21 watt special purpose DRL, Paine calculates the per vehicle cost of supply and installation, globe replacement, and additional fuel consumption. Two installation costs are calculated for each option: the cost of retrofitting and the cost of factory fitting.

Paine (2003) uses Koornstra et al.'s (1997) cost estimates for fuel consumption, which are based on the assumption that low beam headlights require 55 watts each and special purpose DRL typically require about 21 watts each. According to this method, fuel consumption will be increased by 0.15 litres per 100 km for low beam headlight DRL use and approximately 0.08 litres per 100 km for special purpose DRL. This is less than was calculated by the LTSA, primarily because the energy load of DRL was estimated by the LTSA to be about 100 watts per globe.

8.2.2 Benefits

Paine (2003) estimated upper and lower crash savings for Australia. Paine's (2003) upper crash rate reduction estimate was 25%, 20% and 12% for multiple-party daytime fatal, injury and property damage crashes respectively. This was based on Koornstra et al.'s latitude based predictions for Europe. Paine's lower estimates were a 7% reduction in all multiple-party daytime crashes, based upon the NHTSA's (2000) report.

Paine (2003) also considered reductions in the rates of pedestrian crashes. An upper reduction estimate of 28% in daytime pedestrian fatalities (NHTSA, 2000) and a lower reduction estimate of 9% (Bergkvist, 2001) was adopted.

Paine then uses NSW crash data to determine upper and lower estimates of what the percentage reduction in all crashes might be if DRL were introduced. The RTA's Economic Analysis Manual (RTA, 1998) was employed to assign a per vehicle dollar value to the crash reductions.

8.2.3 Paine's Benefit-cost ratio

Using the lowest estimate of benefits, benefits outweighed costs for only factory fitted special purpose DRL, with a ratio of 1.88. The use of automatically activated low beam headlights as DRL was found to be more costly than beneficial for both retro-fitted and factory fitted options, with ratios of 0.07 and 0.66 respectively. Special purpose retrofitted DRL were also found not to be cost effective, with a benefit-cost ratio of 0.47.

Based on high estimates of benefits however, factory fitted and retrofitted DRL of both types were shown to have greater benefit than cost associated with their use. Benefit-cost ratios ranged from 1.84 for retrofitted special purpose DRL to 18.95 for factory fitted automatically activated low beam headlights. Pain does warn however, that applicability of the ratios for low beam headlights in Australian conditions is questionable.

9. Benefit-cost analysis of DRL options in Australia

The process used for the benefit-cost analysis in this report is outlined in this chapter. The full process is described in detail in Appendix A.

9.1 Overview of method

The four options for DRL that were considered in the benefit-cost analysis are:

Model 1 (ADR full time):	All new vehicles fitted with purpose-designed DRL which operate whenever the engine is running, unless night-lights are operating.
Model 2 (low beam):	Drivers are required to drive around at all times with headlights on low beam.
Model 3 (ADR sensor):	All new vehicles fitted with purpose-designed DRL with a light-sensitive triggering device so that they only operate under conditions of low ambient illumination when night-lights are not operating.
Model 4 (limited low beam):	Drivers are required to use their headlights on low beam in the periods immediately prior to sunset and following sunrise.

The process used to estimate the costs and the benefits was as follows.

9.1.1 Estimating the costs

Estimate average amount of time spent travelling during daylight hours, during dawn and dusk conditions and during adverse weather to estimate how long lights are likely to be required under different models.

1. Determine probable capital costs and power requirements associated with different DRL models.

2. Estimate average additional fuel requirements under different models.

3. Estimate average running costs associated with different models.

4. Estimate average total costs associated with different models over the lifetime of a vehicle.

9.1.2 Estimating the benefits

1. Determine the annual number of crashes in the target category, ie multiple-party excluding rear-end crashes occurring during daylight, dawn or dusk, using Victoria as a basis.

2. Determine reduction factors for different jurisdictions, based on latitude.

3. Estimate the annual value of the estimated crash reductions in Victoria by applying Bureau of Transport Economics cost estimates.

4. Estimate the annual value of crash reductions in other Australian jurisdictions by applying adjustments for latitude and the size of the vehicle fleet.

5. Adjust the benefits for each of the DRL models.

6. Estimate the average value of crash savings over the lifetime of a vehicle.

9.1.3 Conducting the economic analysis

1. Calculate the net present value (NPV) by subtracting lifetime average costs from lifetime average benefits.

2. Calculate benefit-cost ratio by dividing lifetime total benefits by lifetime total costs.

9.2 Estimating the cost of providing DRL in Australia

Day to day travel data shows that car drivers spend an average of approximately 160 hours per year driving. Crash data suggests that dawn and dusk crashes comprise 8% of target crashes, and crashes involving wet pavements are an additional 15.3% of target crashes. It has been assumed that travel times in these conditions are in proportion to the crashes occurring during these times. Under Model 4 (limited low beam), vehicle lights will operate for an average of only 13 hours per year. Under Model 3 (ADR sensor) lights will operate for 13 hours during dawn or dusk conditions and 24 hours during conditions of low ambient illumination.

Data on the costs of providing DRL was taken from a report on the benefit-cost analysis of DRL based on Canada's first year of experience with DRL-equipped vehicles (Lawrence, 1995). Although this report is relatively dated it is the best readily available source of information. Where possible, adjustments have been made to update estimates, for example, by adjusting for CPI increases. Lawrence investigated a number of options for providing DRL, including parking lights, fog lights and modifications to the headlight system which included estimates of the capital costs and running costs.

The two options relating to modified headlights have been used in the present study. As it happens they were the most expensive and least expensive of Lawrence's options. Reduced intensity low-beam had both higher capital costs and higher operating costs than reduced intensity high beam. Inclusion of the two technological options requires that the DRL Models with dedicated running lights be extended, ie to Models 1A (ADR full time 100W) and 1B (ADR full time 40W), and 3A (sensor 100W) and 3B (sensor 40W). Capital costs were estimated by converting to \$A and adjusting for CPI increases. Fuel consumption was estimated by the procedure followed in the LTSA estimates. Costs net of fuel taxes were assumed to be \$ 0.40 per litre. Allowance was also made for additional light globes required by the additional hours running.

Total annual costs for each of the models are shown in Table 5.

Table 5: Estimated annual costs of selected DRL options

Model	Additional fuel/yr	Additional globes/yr	Total cost/yr
Model 1A (ADR full time 100W) 160 hrs operation	15 litres $6.00	1 set per 2years $10.00	$16.00
Model 1B (ADR full time 40W) 160 hrs operation	6 litres $2.40	1 set per 2 years $10.00	$12.40
Model 2 (low beam 200W) 160 hrs operation	30 litres $12.00	1set per 2 years $10.00	$22.00
Model 3A (ADR sensor 100W) 37 hrs operation	4 litres/year $ 1.60	1 set per 9 years $2.20	$3.80
Model 3B (ADR sensor 40W) 37 hrs operation	2 litres $0.80	1 set per 9 years $2.25	$3.05
Model 4 (limited low beam 200W) 13 hrs operation	3 litres $1.20	1 set per 26 years $ 1.35*	$2.55

*Calculated on the basis of 1 extra set of globes required during the life of the car, assumed to last 15 years.

9.3 Estimating the value of crash reductions with DRL in Australia

Victorian crash data was chosen as the basis for estimating crash reductions as it has internet access, allowing ready extraction and manipulation of the data, and a detailed classification of crashes by road user movements, which allows identification of the relevant crash types. Data from 1999-2002 were examined. Conspicuity-related crashes during daylight averaged 114 fatal crashes, 1495 serious injury crashes, and 3264 other injury crashes per year.

Estimated crash reductions for each jurisdiction were calculated using the relationships developed by Koornstra et al. (1997), ie:

% decrease in fatalities $0.00331(\text{degrees})^{2.329}$

% decrease in serious injuries $0.00279(\text{degrees})^{2.329}$

% decrease in all crashes $0.00166(\text{degrees})^{2.329}$

The expected reductions for crashes of different severities is shown in Table 6.

Table 6: Expected reductions in crashes of different severities in Australian jurisdictions following introduction of DRL according to Koornstra et al.'s (1997) formulation

Jurisdiction	Latitude	Expected reduction (%), fatal crashes	Expected reduction (%), serious injury crashes	Expected reduction (%), other injury crashes
Victoria	37° S	14.87	12.53	7.46
NSW	34° S	12.21	10.29	6.12
Queensland	27° S	7.14	6.02	3.58
Western Australia	32° S	10.60	8.94	5.32
South Australia	35° S	13.06	11.01	6.55
Tasmania	43° S	21.09	17.78	10.58
ACT	35° S	13.06	11.01	6.55
Northern Territory	12° S	1.08	0.91	0.54

The value of crashes prevented in Victoria was estimated by applying the costs of crashes of different severity provided by the Bureau of Transport Economics (BTE, 2000), updated by CPI increases and rounded to the nearest $1000. The values used in the present analysis are:

Fatal crash $1,673,000

Serious injury crash $413,000

Minor injury crash $14,000

Estimated crash savings in Victoria are shown in Table 7.

Table 7: Value of crashes prevented in Victoria

Crash Severity	Number of crashes	Reduction Factor	Number of crashes prevented	Value of crashes prevented
Fatal	114	14.87%	17	$28,441,000
Serious Injury	1495	12.53%	187	$77,231,000
Other Injury	3264	7.46%	243	$3,402,000
Total	4873	9.17%	447	$109,074,000

The value of the expected crash reductions in each of the jurisdictions has been estimated by taking the values of crashes in each category prevented in Victoria and adjusting them for the number of registered vehicles and latitude applying to the other jurisdictions.

The adjustment for number of vehicles consisted of multiplying the crashes prevented in Victoria by the term:

(Registered vehicles in Jurisdiction A/Registered vehicles in Victoria).

The adjustment for latitude consisted of multiplying the number of crashes prevented in Victoria by the term:

(Estimated reduction in Jurisdiction A/Estimated reduction in Victoria).

There is some question as to whether reductions in less serious injuries can be expected with DRL, so an upper value of the estimate was calculated including the other injuries, and a lower value estimated using only fatal and serious injury crashes. These values were divided by the number of registered vehicles in each jurisdiction to provide an estimate of the average benefits per vehicle for comparison with the costs developed in Table 8.

Table 8: Value of DRL to individual vehicle operators

Jurisdiction	Upper value(UV)	Lower value(LV)	Number of vehicles	UV per vehicle	LV per vehicle
VIC	$109,074,000	$105,672,000	3,310,944	$32.94	$31.92
NSW	$101,067,968	$97,915,675	3,751,483	$26.94	$26.10
QLD	$37,172,419	$36,013,018	2,366,880	$15.71	$15.22
WA	$31,751,441	$30,761,119	1,359,145	$23.36	$22.63
SA	$29,755,387	$28,827,322	1,034,663	$28.76	$27.86
TAS	$15,488,508	$15,005,424	326,247	$47.47	$45.99
ACT	$5,759,107	$5,579,482	201,236	$28.62	$27.73
NT	$229,055	$221,911	100,381	$2.28	$2.21
Total	$330,297,887	$319,995,950	12,450,979	$26.52	$25.70

Table 8 shows that there is little difference between the upper and lower estimates. A value of $26.00 was therefore selected as representative.

The assumptions relating to the crash savings for the different models are as follows:

Model 1 (ADR full time) and Model 2 (low beam): Since the lights operate all the time, these lights would be expected to deliver the full range of crash reductions estimated above. However, the evidence is that DRL have little if any effect, except during conditions of low ambient illumination. The crash reductions are therefore likely to be concentrated in the periods around dawn and dusk, and during adverse weather.

Model 3 (ADR sensor): Under Model 3, DRL will automatically be switched on when ambient light reaches a critical level. Provided an appropriate triggering point is set, Model 3 should capture most of the benefits of Models 1 (ADR full time) and 2 (low beam). This assumption is prompted by Cobb's results (Cobb 1999), in which it was clear that DRL only made a difference under "cloudy" conditions, although "cloudy" was not tied to any particular threshold level for ambient light. This point is dealt with in detail in the critique of Cobb's work in Section 3.4.

Model 4 (limited low beam): Model 4 requires drivers to turn on their headlights in the periods before sunset, and to continue to use them in the period after sunrise. This would capture similar benefits to the other models in the pre-dusk and post-dawn periods, but not the benefits which result from headlight use during adverse weather. The benefits associated with this model have therefore been adjusted downwards. The Victorian CrashStats results show that 15.3% of target crashes occur on wet roads, and 8% occur during dusk or dawn.

Under Model 4, the crash reductions expected are therefore [8.0/(15.3+ 8.0)] = 0.34 (ie 34%) of the reductions expected under the other models.

9.4 Benefit-cost analysis

A life of 15 years has been assumed for a new motor vehicle. Table 9 shows, for each model, the capital costs, and the running costs summed over the life of the vehicle, using a discount rate for future running costs of 7%. Crash savings have also been summed over the life of the vehicle, also discounted by 7%. The Net Present Value is calculated by subtracting running costs and capital costs from net benefits, and the benefit-cost ratio by dividing the net benefits by the sum of the running costs and capital costs.

All models have a positive NPV and a benefit-cost ratio greater than 1. However, the lowest NPVs and benefit-cost ratios are for the Models where the DRL are on all the time during daylight (Models 1A, 1B and 2). Models where the DRL operate only when needed (Model 3A, 3B, and 4) have higher NPVs and benefit-cost ratios, since costs are lower and it has been assumed they will capture all the benefits that the other models would. The savings in running costs for Models 3A (ADR sensor 100W) and 3B (ADR sensor 40W) compared to Models 1A (ADR full time 100W) and 1B (ADR full time 40W) suggest that it is worth investing in the light-activated sensor to control the lights.

Model 1A (ADR full time 100W) would be expected to deliver the full range of benefits, but has relatively high capital costs and running costs. It is fully automated, so there would be no problems with compliance or flat batteries from leaving lights on.

Model 1B (ADR full time 40W) also delivers the full range of benefits but at lower capital and running costs than 1A. It would also deliver the full range of benefits, and is fully automated.

Model 2 (low beam) involves no capital costs but relatively high running costs. It has been assumed it will deliver the full range of benefits, but there may be problems with compliance through people forgetting to turn on their lights, or choosing not to comply. In the French trial discussed in Section 4.2.5 (Lassarre, 2002), use rates in built-up areas remained low. It may also be anticipated there would be a problem with people forgetting to turn off their lights during the day when the vehicle was stopped. Cost estimates in relation to these issues have not been attempted in the present investigation.

Model 3A (ADR sensor 100W) is assumed to deliver the full range of benefits. While we can be confident that more benefits will be delivered during low lighting conditions than during normal conditions, it is still possible that crash reductions may occur during normal lighting conditions in some circumstances. More evidence is required on this point. The system is fully automated, so problems with compliance and leaving lights on should be avoided.

Similar points apply to Model 3B (ADR sensor 40W), which has lower capital costs and running costs than does Model 3A.

It has been assumed that Model 4 (limited low beam) will prevent crashes only during the dawn and dusk periods. The benefits are therefore lower than those for other models, but there are low running costs and no capital costs, so the benefit-cost ratio is relatively high. Some means would have to be put into place to encourage compliance – perhaps radio announcements and reminders at the appropriate times would be sufficient to achieve reasonable compliance levels.

Table 9: Benefit-cost analyses associated with the different DRL models

Model	Capital costs $	Lifetime running costs $	Lifetime benefits $	NPV $	Benefit/ Cost ratio
Model 1A (ADR full time 100W) 160 hrs operation	30.00	145.76	236.86	61.10	1.35
Model 1B (ADR full time 40W) 160 hrs operation	4.00	112.96	236.86	119.90	2.03
Model 2 (low beam 200W) 160 hrs operation	0.00	200.42	236.86	36.44	1.18
Model 3A (ADR sensor 100W) 37 hrs operation	50.00	34.62	236.86	152.24	2.80
Model 3B (ADR sensor 40W) 37 hrs operation	24.00	27.79	236.86	185.07	4.59
Model 4 (limited low beam 200W) 13 hrs operation	0.00	23.32	80.62	57.39	3.47

The assumption that Models 3A and 3B will deliver the full range of benefits that Models 1 and 2 will deliver has been prompted by the available evidence, particularly Cobb's finding that DRL improve conspicuity only under low lighting conditions (Cobb 2001, see Section 3.4). The corollary of this assumption is that most of the benefits under Models 1 and 2 would also occur under these conditions, and that to realise the predicted totals, crashes would have to be reduced by approximately 50% during the target periods. These assumptions are probably unrealistic, but necessary in view of the lack of any evidence linking extent of crash reduction due to DRL to the ambient illumination at the time of the crash. It is therefore possible that Models 3A and 3B will deliver lesser crash reductions than Models1A, 1B or 2.

The extent to which light-responsive DRL capture the full benefits of full-time DRL will depend critically on the triggering threshold for the DRL. A high triggering threshold will result in DRL operating for less of the time, capturing fewer of the benefits but imposing lower operating costs. A lower triggering threshold would be expected to capture more of the benefits at the expense of higher operating costs. Thus impact on the benefit-cost ratio will depend on

- the proportions of crashes which can be prevented under different light levels; and
- the triggering threshold for the DRL.

It is not possible to estimate these relationships on the basis of current knowledge, and so the assumption that all the benefits of DRL will be obtained under conditions of low ambient light has been retained for the purpose of the analysis.

9.5 Comparison with LTSA and Paine's benefit-cost analyses

When faced with the task of estimating the effect of an untried countermeasure in a traffic system, there is no one correct way of going about it. Investigators will attempt to estimate the likely outcomes based on their interpretation of what has happened elsewhere and the data sources they have available which describes behaviour and crash outcomes in the traffic system in question.

It is therefore instructive to compare the benefit-cost analysis described above with those carried out recently for the LTSA in New Zealand (LTSA, 2000), and by Paine for the NRMA and RACV (Paine, 2003).

9.5.1 Estimating crash reductions

The present report and the LTSA approach were similar in that they applied Koornstra et al.'s latitude-based formulae to estimate likely crash reductions in different parts of the country. Paine applied the reduction factors only to NSW data, but applied Koornstra et al.'s estimates for Europe as a whole as his upper limit, and a US estimate of a 7% reduction as the lower limit. Paine himself points out that the Koornstra et al. reduction factors for Europe are probably double what could be expected in Australia, but then suggests that dedicated DRL with a more effective light distribution should enable the full benefits estimated in Europe to be realised. This is a questionable claim. The net result of this is that Paine's higher estimates of crash savings are considerably greater than in the other two papers.

In the present paper, the latest BTE estimates of the cost of crashes (BTE, 2000) have been used, whereas Paine has used older cost estimates taken from the RTA Economic Analysis manual. The main difference between the costs is that the BTE substantially increased the cost of serious injury crashes in these latest estimates, from approximately $100,000 to over $400,000 to take account of the long-term care of disabled persons. This represents a large increase in the largest cost category. No reduction in property damage only crashes was included in the present study, as it is not certain to what extent they are realised by DRL.

9.5.2 Estimating the costs of providing DRL

The options explored in the present study assumed either that DRL would be installed at time of manufacture, or normal lighting equipment would be used. No provision was made for DRL fitted to existing vehicles. The LTSA project similarly considered only existing headlights. Paine considered three cases – existing headlights, DRL fitted at time of manufacture and retro-fitted DRL, the latter having much higher cost. Paine's estimated capital costs are slightly higher than those in the present paper, but the difference is not sufficient to materially affect the outcome of the analysis.

Only the present paper explores the issue of costs with light-sensor control of the DRL. It is evident that there are substantial fuel savings to be made with this option; however it must be recognised that the crash savings might be reduced, though it is not possible to say by how much.

What is clear from both the present and Paine's analyses is that dedicated DRL with lower power requirements will result in substantial savings.

It is also worth pointing out that Paine's consideration of the characteristics of different lighting options would rule out options 1A and 3A in the present analysis as they depend on a modified low-beam technology.

9.5.3 Common ground

Although the three benefit-cost analyses differ in their approaches and assumptions, some points of agreement may be discerned.

First, any scheme which relies on full-time daytime use of dipped headlights seems likely to produce a benefit-cost ratio close to 1.

Second, the present review and Paine agree that considerable fuel savings will result from using dedicated DRL with lower power requirements. As a result, options which incorporate DRL have benefit-cost ratios in excess of 1, the ratio depending on the assumptions regarding the crash savings which are likely and the method used for costing these crashes.

10. Unresolved issues

10.1 Estimating crash rates

It is clear from the body of evidence presented in Section 4 that there is high probability that DRL would reduce daytime multiple-party crashes in Australia. However, it is not clear by how much they would be reduced. Although Koornstra et al. (1997) provide a model based on latitude which gives a good fit to the data on which it is based, other studies have provided anomalous results. Generally these anomalous results have resulted in greater reductions for regions close to the equator than the Koornstra et al. model would predict.

In Victoria, most daytime vehicle-vehicle crashes happen in the metropolitan area, and the population distribution in other states suggests that similar patterns would be found there. It would be necessary to demonstrate that DRL produce crash reductions in built-up areas before we can be confident they would be effective in Australia. In Section 4.2, Bergkvist's results indicated a significant reduction in vehicle-vehicle crashes in urban areas, but not in rural areas. Lassare (2002) found reductions in fatal and serious injury crashes on rural highways, but did not analyse urban data because only low levels of voluntary daytime headlight use were achieved in towns. This issue may perhaps be resolved to some extent by detailed examination of the sources on which Elvik's and Koornstra et al.'s reviews are based.

Further confounding this point is the uncertainty about the extent to which property damage only crashes are affected by DRL. Koornstra et al. concluded that property damage crashes are reduced, but at a lesser rate than fatal or injury crashes. However, Lassarre (2000) found significant reductions only in fatal and serious injury crashes. Note that reductions in property damage crashes have not been included in the present benefit-cost analysis. If DRL do in fact have an impact on these crashes, this would further increase the associated benefits.

In addition, there are complex issues relating to differences in the reporting and classification of injury crashes in overseas jurisdictions which make interpretation difficult. It is likely that different jurisdictions have different criteria for reporting crashes. Even when criteria for reporting and classifying crashes are superficially similar, there may be differences in how police or road authorities apply these criteria in practice. These points also apply within Australia, limiting the precision with which predictions about reducing crash rates can be made.

Although the estimate of crash reductions in the present study is subject to a great deal of uncertainty, it is not likely to be greatly improved by refining the assumptions or the benefit-cost analysis. The basic issues are the variability amongst the results of existing studies and inherent uncertainty about how effective DRL will be in Australia.

10.2 Estimating the cost of providing DRL

Paine (2003) gives better-researched and more up-to-date estimates of the costs of providing DRL than were possible in the present investigation, although both studies are reasonably close in their estimates.

The issue of the length of time for which light sensor-activated DRL would operate is critical for determining operating costs. It was not addressed by Paine, and was inferred from assumptions about light conditions at the time of crashes in the present investigation. A more accurate estimate could be obtained if daylight values for different times of year were available. So far, the research team has not succeeded in identifying such data. That said, a more accurate estimate is unlikely to change the conclusions that would be drawn from the benefit-cost analysis. Inspection of Table 9 shows that for the options involving sensor-operated DRL (Models 3A and 3B), even if the lifetime operating costs were doubled, the NPV would still be positive and the benefit-cost ratios greater than 1.0. An accurate estimate of the capital costs of providing a sensor-control for DRL is also required.

The environmental costs of the additional emissions have not been taken into account, but are likely to be relatively modest.

10.3 Road user acceptance of DRL

One of the concluding points raised by Koornstra et al. is a discussion of the acceptability of DRL on the part of road users. They suggest that it is difficult for drivers to accept that DRL can assist visibility under good conditions as they know from experience that they can see what they need to see to drive effectively. However, as Koornstra et al. point out, failure to see vehicles in time to avoid crashes has emerged as a major factor in many in-depth studies (for example, see Section 3.3 above).

Scepticism regarding the effectiveness of DRL has held up the implementation of DRL in many European countries. This has been compounded by apparently inconsistent results from different studies – inconsistent, that is until Koornstra et al.'s re-analysis put everything on a consistent footing. Nevertheless, scepticism on the part of road users and their elected representatives is likely to remain a barrier to wider implementation, especially in the more southerly countries of Europe where the benefits are likely to be less.

Strongest opposition has come from motorcyclist, cyclist and pedestrian organisations who fear they may be disadvantaged by a move to have universal DRL obligations. However, Koornstra et al.'s analyses indicate that motorcyclists and pedestrians would benefit by about the same amount as car occupants.

DRL in Europe have generally taken the form of a universal obligation to use lights during the day. Two points need to be made in relation to this issue. First, for the majority of drivers, this has meant using headlights on low beam during the day. Many jurisdictions have begun by requiring partial compliance with DRL, for example, during winter (Finland), or on the major road network only (Hungary), to establish the behaviour, and then extended the obligation to cover all times or all roads.

Second, Cobb's (1999) investigation of DRL under changing ambient illumination strongly suggested that benefits were likely to be greatest (if not confined to) periods of low ambient illumination. The road using public may therefore be substantially correct in their scepticism regarding the effectiveness of full-time DRL obligations. It would be useful to know the relative crash reductions achieved by DRL in dawn and dusk conditions, during poor weather, and during good conditions.

The points of immediate relevance for Australia to emerge from this discussion are to further reinforce the case for light-sensor activated DRL which come on only when needed. If the benefits of DRL are largely confined to periods of low natural illumination, then they appear to be the most cost-effective option. Greater acceptability on the part of the public would be an added advantage.

The use of dedicated DRL with limited light output rather than dipped headlights should eliminate the problem of masking vulnerable road users and so make them more acceptable to these groups.

It follows from the discussion in this section that the introduction of DRL via the design rules or other means should be accompanied by a concerted campaign to ensure that the public understands the basis for their effectiveness and the benefits that are likely to flow from them.

10.4 Managing transition

If DRL are to be introduced in Australia, then it is essential that arrangements be put in place which addresses all the existing vehicles on the road that do not have the benefit of this technology. It would take several years to replace the existing fleet with new vehicles equipped with factory-fitted DRL. The question then remains of what to do with vehicles which pre-dated DRL.

There appear to be three options.

1. Allow existing vehicles to continue as they are. Existing vehicles would not benefit from DRL unless owners choose to retrofit DRL or their drivers to use dipped headlights on a voluntary basis. Although full-time dipped headlight operation produces benefit-cost ratios close to 1 (see Section 8.5), voluntary use might give rise to better outcomes if use is restricted to those conditions where DRL is of greatest benefit. The costs of inadvertently leaving lights on, or alternatively, the additional costs required to fit an alerting device to warn that lights were left on, would eat into these meagre benefits.

2. Require all vehicles to be fitted with DRL, similar in function to whichever DRL model is selected. Although this would ensure that all vehicles benefit from DRL, this approach is unlikely to be cost-effective, especially for older vehicles.

3. Require drivers of older vehicles to use dipped headlights when DRL on newer vehicles are lit. In the case of the full time operation option, this would require that dipped headlights be operated all the time, which is likely to produce a benefit-cost ratio close to 1. In the case of the light-responsive sensor option, the benefit-cost ratio is probably considerably higher, but there is uncertainty about the likely degree of compliance. As enforcement is likely to be difficult, a high degree of voluntary compliance is essential. For both cases, the costs of retrofitting a device to warn of lights left on, or the costs of inadvertently leaving lights on, would reduce the benefit-cost ratios.

It is beyond the brief of the present paper to solve these issues, but it is important that they are recognised as part of the arrangements which have to be put in place if it is decided that DRL should be introduced in Australia.

11. Conclusions

1. There is a substantial body of evidence which shows that DRL reduce daytime crashes. However, there is considerable variation in the size of the reduction reported in different studies.

2. Most studies simply report overall reductions. As a result, three issues remain unresolved, or have little data to support them. Resolution of these issues would clarify the likely effects of DRL on crashes in Australia, or would help decide between having full-time DRL and DRL which operate only under conditions of low illumination. They are:

   - What is the relative effect in built-up areas and open country? Most daytime crashes in Australia occur in metropolitan areas.

   - How much of the crash savings occurred during the dawn/dusk period, and how many during conditions of low ambient lighting? This would clarify the case for full-time or light-responsive DRL.

   - How have different crash types (cross traffic, right (or left) turn against, head-on, etc) been affected?

3. Empirical work has shown which type of DRL is most suitable. Dipped headlights, even with reduced light output, are not a good choice as much of the light is directed towards the road surface, which is ineffective during daytime (although effective at night). The technically best option appears to be dedicated DRL with an intensity of 1200 candelas. The introduction of an ADR would also appear to be preferable for non-technical reasons. Although the introduction of an ADR is associated with long lead times, compulsory usage laws have no State support and are associated with compliance and enforcement problems.

4. Opinion in the different jurisdictions around the nation indicates majority support for DRL, although it should be borne in mind that this represents the views of individual officials and not, at this stage, departmental policy. Some of the respondents contacted suggested that a clearer indication of the likely benefits in Australia would be required before full support would be forthcoming. Most emphasised that they favoured a national approach rather than action by individual jurisdictions, and some were conscious of the benefits of aligning practice with that in the larger motor vehicle markets. A majority indicated a preference for full-time operation of DRL.

5. The benefit-cost analysis suggested the costs of providing DRL would be considerably reduced if the DRL operated only in conditions of low lighting. However, it is not possible to estimate the extent to which the crash reductions might be reduced under this option (refer Conclusion 2). In view of the jurisdictions' preference for full-time operation, evidence in support of this option would have to be persuasive before it was adopted.

6. An appropriate course of action for Australia will be to await the outcome of the determinations currently taking place in Europe in relation to DRL, and which are expected to be complete by the end of the year (see Section 1.1). At that stage it would be

appropriate to give the issue full consideration in the light of the European decision, and the outcomes of Paine's and the present analysis.

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APPENDIX A: Benefit-cost analysis of DRL options in Australia

A1 Overview of method

The project proposal specifies four options for examining the effects of DRL:

Model 1 (ADR full time):	All new vehicles fitted with purpose-designed DRL which operate whenever the engine is running, unless night lights are operating.
Model 2 (low beam):	Drivers are required to drive around at all times with headlights on low beam.
Model 3 (ADR sensor):	All new vehicles fitted with purpose-designed DRL with a light-sensitive triggering device so that they only operate under conditions of low ambient illumination when night-lights are not operating.
Model 4 (limited low beam):	Drivers are required to use their headlights on low beam in the periods immediately prior to sunset and following sunrise.

The process used to estimate the costs and the benefits was as follows.

Estimating the costs

1. Estimate average amount of time spent travelling during daylight hours, during dawn and dusk conditions and during adverse weather to estimate how long lights are likely to be required under different models.

2. Determine probable capital costs and power requirements associated with different DRL models.

3. Estimate average additional fuel requirements under different models.

4. Estimate average running costs associated with different models.

5. Estimate average total costs associated with different models over the lifetime of a vehicle.

Estimating the benefits

1. Determine the annual number of crashes in the target category, that is, multiple-party (excluding rear-end) crashes occurring during daylight, dawn or dusk, using Victoria as a basis.

2. Determine reduction factors for different jurisdictions, based on latitude.

3. Estimate the annual value of the estimated crash reductions in Victoria by applying Bureau of Transport Economics cost estimates.

4. Estimate the annual value of crash reductions in other Australian jurisdictions by applying adjustments for latitude and the size of the vehicle fleet.

5. Adjust the benefits for each of the DRL models.

6. Estimate the average value of crash savings over the lifetime of a vehicle.

Conducting the economic analysis

1. Calculate the net present value (NPV) by subtracting lifetime average costs from lifetime average benefits.

2. Calculate benefit-cost ratio by dividing lifetime total benefits by lifetime total costs.

A2 Estimating time for which DRL are likely to operate

Hours spent driving

Average travel during daylight was approximated by taking the average number of minutes spent driving in Australia from a survey of day travel in Australia (Anderson, Montesin & Adena, 1989). Although now somewhat dated (fieldwork was carried out in 1984-5), this study remains the only source of national data on exposure by different forms of road transport, and the only comprehensive source for which hours of travel can be broken down by times of day. The daily average minutes spent driving between the hours of 06.00 and 18.00 was 34.30 minutes for men and 17.45 minutes for women, which was averaged to produce an estimate of 25.9 minutes a day, or 9,453.5 minutes per year. This is equivalent to 157.6 hours, rounded to 160 hours, or three hours per week.

The equivalent exposure for night-time driving is approximately 35 hours, or approximately 40 minutes a week. This makes a total average time spent driving of three hours 40 minutes per week. Drivers under Models 1 (ADR full time) and 3 (ADR sensor) therefore will be assumed to be using DRL for 160 hours/year on average.

From CrashStats, it was found that 8% of the target crashes occurred during dawn or dusk. Assuming that traffic exposure during poor daylight conditions is proportional to the proportion of crashes in dawn and dusk results in an estimate of 8% use of DRL. Thus under Model 4 (limited low beam), vehicles would use their headlights for an average of 12.8 hours per year, which can be conveniently rounded up to 13 hours per year.

From the same analysis, wet pavement crashes made up 15% of the total. If it is assumed that poor visibility conditions are in proportion to the number of wet pavement crashes, then under Model 2 (low beam), DRL will operate because of adverse weather for approximately 24 hours per year, in addition to 13 hours per year for dawn and dusk operation, making a total of 37 hours per year.

A3 Costs of providing and maintaining DRL under different models

In considering the costs of providing DRL under the four different models, only the capital costs of providing the basic equipment and the running costs in terms of bulb replacement and additional fuel costs will be considered. It is assumed there will be no additional policing costs or educational costs.

The best technical solution for DRL, as the material reviewed in Section 3 has shown, is a light with an output of 1200 candelas. It has been assumed that this output could be achieved with lights that require 20 watts per lamp. Further investigation is required to determine the precise wattage requirement for the lamps. The important point for the analysis is that the power requirement of dedicated DRL (40 watts) is a considerable reduction compared to the requirements to power the vehicle's complete lighting system (approximately 200 watts), which results in considerably lower costs and higher benefit-cost ratios.

Capital costs

Transport Canada conducted a retrospective benefit-cost analysis of DRL in that country, based on crashes involving the first year's crash experience of DRL equipped vehicles (Lawrence 1995). One aspect of this analysis is an exhaustive listing of the costs of different types of running lights. Although this source is now somewhat dated, the research team found no other published source which presented costed options for different types of DRL. The cost estimates are close to those presented by Paine (2003) in his evaluation. It is acknowledged that up to date cost estimates, taking into account current technology and the possibility of a light-responsive activating sensor, are a priority for future work.

The two options relating to modified headlights (reduced intensity low beam and reduced intensity high beam headlights) have been used in the present study. As it so happens, the upper estimate of reduced-intensity low beam is the most expensive of the options investigated, and reduced intensity high-beam is the least expensive. These costs have therefore been adopted as the upper and lower limits for providing DRL. The costs, net of mark-ups and taxes are $C 21.40 and $C 2.75 respectively, in 1993 dollars. Adjusting these costs to reflect 2002 Australian dollars produces estimates of $29.66 and $3.81 respectively, rounded up to $30.00 and $4.00 respectively.

These adjustments are based on an increase in CPI from 109.3 to 137.6 over the period June 1993 to June 2002, and an exchange rate of $C 0.90 per $A 1.

Two versions of Model 1 (ADR full time) and Model 3 (ADR sensor), the Models with dedicated DRL, will therefore be required for the benefit-cost analysis. The versions with the reduced-intensity low beam lighting will be designated Model 1A (ADR full time 100W) and Model 3A (ADR sensor 100W) and those with the reduced density high beam lighting Model 1B (ADR full time 40W) and Model 3B (ADR sensor 40W).

Light sensing technologies have now matured to the extent where sensors to detect falling light levels could be incorporated into the design of the vehicle at little extra cost. It has been assumed for the purposes of the analysis that the sensor and additional wiring required would be $20. Thus the capital costs for Model 3A (ADR Sensor 100W) have been assumed to be $50.00, and for Model 3B (ADR sensor 40W), $24.00.

Model 4 involves drivers using their existing headlights at specified times, and therefore involves no capital costs.

Running costs

The major difference amongst the models is in terms of running costs. Models 2 (low beam) and Model 4 (limited low beam) involve running conventional headlights on low beam, whereas Models 1A (ADR full time 100W), 1B (ADR full time 40W), 3A (ADR sensor 100W) and 3B (ADR sensor 40W) involve the provision of a DRL function with lower light output. Models 3A, 3B and 4 (limited low beam) would involve only limited use of the lights, and would both require less fuel and less bulb replacement.

For Models 1A (ADR full time 100W), 1B (ADR full time 40W) and 2 (low beam), the lights would operate at all times, and therefore running costs should be based on an estimate of the number of hours for which vehicles are in operation during daylight. Average daytime running under these models has been estimated at 160 hours/year (see Section A2 for sources and estimation procedure).

For Models 3A (ADR sensor 100W) and 3B (ADR sensor 40W), the lights operate only in the pre-sunset and post-dawn periods, and during inclement weather. This has been estimated at an average of 37 hours per year (see Section A2).

For Model 4 (limited low beam), lights would operate only during the dawn or dusk periods. Average travel under these conditions has been estimated at 13 hours/year.

Conventional lighting imposes a load of 200W on the vehicle's electrical system. Models 1A and 3A utilise reduced low beam lighting, and are estimated to impose an electrical load of 100 W, whereas Models 1B and 3B utilise reduced high beam lighting, and are estimated to impose a load of 40 W (see Lawrence, 1995, Table 4, p7).

The method used to calculate the additional fuel required has been adapted from that adopted in the LTSA analysis (LTSA, 2000), which is itself based on methods developed in the Canadian evaluation. According to Lawson (1986), the energy value of petroleum is 8888.9 watt-hours per litre. The efficiency of petrol engines is widely accepted as being 22%, and the efficiency of electrical generators in vehicles as being 55%. The electrical energy which can be produced per litre of fuel may then be estimated as follows:

Efficiency of electrical generation via car engine	=	thermal efficiency of petrol motor x efficiency of generators
	=	0.121
Electricity generated from fuel	=	8888.9 x 0.121
	=	1075.56 Watt Hours/litre.

Additional fuel required under the different models is therefore:

Model 1A (ADR full time 100W) = (100x 160)/1075.56) = 14.87

Model 1B (ADR full time 40W) = (40x 160)/1075.56) = 5.95

Model 2 (low beam) = (200x 160)/1075.56) = 29.75

Model 3A (ADR sensor 100W) = (100x 37)/1075.56) = 3.44

Model 3B (ADR sensor 40W) = (40x 37)/1075.56) = 1.38

Model 4 (limited low beam) = (200x 13)/1075.56) = 2.41

From Lawrence (1995) it is assumed that globes have an average operating life of 340 hours. Inspection of retail outlets shows that the price of a standard headlight replacement globe is $11.90, inclusive of GST. A base price of $10.00 has therefore been assumed.

According to the RACV web site, petrol in Australia is subject to 38.1 cents/litre fuel excise, and to 10% GST calculated once the excise has been added to the retailer's price. A price to the motorist of 85 cents/litre has been assumed for the purposes of the benefit-cost analysis, typical of Melbourne prices since the end of the Iraq war. This is equivalent to a price excluding taxes of 39.1 cents/litre, rounded to 40 cents/litre.

Additional fuel costs imposed by DRL are estimated by multiplying estimated hours of operation.

Table 1A: Estimated annual costs of selected DRL options

Model	Additional fuel/yr	Additional globes/yr	Total cost/yr
Model 1A (ADR full time 100 W) 160 hrs operation	15 litres $6.00	1 set per 2years $10.00	$16.00
Model 1B (ADR full time 40 W) 160 hrs operation	6 litres $2.40	1 set per 2 years $10.00	$12.40
Model 2 (low beam 200 W) 160 hrs operation	30 litres $12.00	1set per 2 years $10.00	$22.00
Model 3A (ADR sensor 100 W) 37 hrs operation	4 litres/year $ 1.60	1 set per 9 years $2.20	$3.80
Model 3B (ADR sensor 40W) 37 hrs operation	2 litres $0.80	1 set per 9 years $2.25	$3.05
Model 4 (limited low beam 200 W) 13 hrs operation	3 litres $1.20	1 set per 26 years $ 1.35*	$2.55

*Calculated on the basis of 1 extra set of globes required during the life of the car, assumed to last 15 years.

A4 Estimating the benefits of DRL in Australia

The benefits which might arise from the application of DRL in Australia can only be estimated with a low degree of confidence, for three main reasons. First, as we have seen in the review above, there is considerable uncertainty regarding the size and nature of the effect from the literature. Second, it is not certain how overseas results would apply in Australia. Third, there are differences in reporting systems in Australia which make it difficult to generalise about effects in injury crashes. States which have superficially similar definitions of injury vary considerably in terms of the numbers of injuries reported in relation to the numbers of deaths (eg, Cairney & Cusack, 1997), and one state does not differentiate between serious and other injuries. A precise and reliable estimate of the numbers of crashes which might be prevented by DRL is therefore not possible.

The requirement for the present study is an indication of the benefits which might arise from DRL in Australia. The study brief specifically called for estimates of the number of fatalities and serious injuries which would be likely to be saved. The approach taken has therefore been to use the most convenient state road authority crash database to estimate the likely reductions in fatal and injury crashes and to extrapolate these to the rest of the country, adjusting for the number of vehicles registered in each jurisdiction and the difference in latitude. Estimates for the average cost of fatal and serious injury crashes in Australia are available (BTE, 2000) which take into account any fatalities and/or serious injuries resulting from a crash in addition to the most serious outcome that defines the crash classification.

A more *precise* process would be to identify numbers of daytime conspicuity-related fatalities and serious injuries in each jurisdiction, and apply the vehicle and latitude-related crash factors directly. However, there is such variation in crash numbers between jurisdictions and such uncertainty about the true effects of latitude on crash rates that it is questionable whether this would produce more *accurate* results.

The estimate of possible crash reductions has been based on crash statistics from Victoria. This jurisdiction has been chosen for a number of reasons. It provides internet access to its crash statistics, and has a comprehensive breakdown of crash types which allows the ready identification of daytime conspicuity-related crashes. It also allows identification of serious injury crashes, which is important because of assumptions related to the analysis. It is the largest jurisdiction whose crash data-base has all these features.

Basic assumptions

1. Only daytime conspicuity-related crashes are likely to be affected by DRL.

2. Fatal and serious injuries are likely to be affected by DRL, but there is some question whether other injuries will be affected as well. Estimates of benefits have therefore been made with and without other injuries included.

3. The Koornstra et al. (1997) crash reduction factors give a realistic estimate of the effects of latitude on crash reductions in different parts of Australia.

4. The proportions of fatal, serious injury and other injury crashes in all jurisdiction are the same as those in Victoria.

5. The dollar estimates of the values of fatal, serious injury and other injury crashes contained in BTE Report No 102 are realistic estimates of the value of crashes likely to be saved by DRL.

6. The latitude of the capital city of each state is an appropriate basis from which to estimate crash reductions for the whole State.

7. The value of DRL to each vehicle operator has been estimated by dividing the total benefits in each state by the total number of registered vehicles.

8. National benefits have been estimated by summing benefits from each state.

Determining the number of relevant crashes in Victoria

Victorian crash data for the period 30th June 1999 to 30th June 2002 were examined. A database query was developed which displayed the numbers of crashes in each severity class (fatal, serious injury and other injury) which resulted from conspicuity-related vehicle-vehicle crashes occurring during daylight.

For the three year period, the totals were 342 fatal crashes, 4485 serious injury crashes and 9792 other injury crashes. The average number of casualties in each class per year is therefore 114 fatal crashes, 1495 serious injury crashes, and 3264 other injury crashes.

Determining the reduction factors for different jurisdictions

According to Koornstra et al., the expected reductions in crashes should be estimated according to the following formulae:

% decrease in fatalities $0.00331(\text{degrees})^{2.329}$

% decrease in serious injuries $0.00279(\text{degrees})^{2.329}$

% decrease in all crashes $0.00166(\text{degrees})^{2.329}$

These factors have been estimated for the different Australian jurisdictions.

Table 2A: Expected reductions in crashes of different severities in Australian jurisdictions following introduction of DRL according to Koornstra et al.'s (1997) formulation

Jurisdiction	Latitude	Expected reduction (%), fatal crashes	Expected reduction (%), serious injury crashes	Expected reduction (%), other injury crashes
Victoria	37° S	14.87	12.53	7.46
NSW	34° S	12.21	10.29	6.12
Queensland	27° S	7.14	6.02	3.58
Western Australia	32° S	10.60	8.94	5.32
South Australia	35° S	13.06	11.01	6.55
Tasmania	43° S	21.09	17.78	10.58
ACT	35° S	13.06	11.01	6.55
Northern Territory	12° S	1.08	0.91	0.54

Expected crash reductions in Victoria

This is based on applying the appropriate Koornstra et al. (1997) reduction factor to the number of daytime conspicuity-related crashes in the Victorian database, then applying the estimated person costs and vehicle costs for each crash severity derived from the BTE report (BTE 2000).

The value of the crashes prevented was estimated by taking the costs associated with road crashes from BTE Report 102 (BTE 2000), and multiplying them by the number of crashes prevented. The costs for each casualty and crash category is $1,652,994 per fatal crash, $407,990 per serious injury crash and $13,776 per minor injury crash. These results are in 1996 dollars. They have been updated to 2002 dollars by applying a factor which reflects increases in the CPI over the same period.

The CPI increase between 1996 and 2002 was 1.2%. The adjusted figures, rounded to the nearest $1000, are:

Fatal crash	$1,673,000
Serious injury crash	$413,000
Minor injury crash	$14,000

Table 3A: Value of crashes prevented in Victoria

Crash Severity	Number of crashes	Reduction Factor	Number of crashes prevented	Value of crashes prevented
Fatal	114	14.87%	17	$28,441,000
Serious Injury	1495	12.53%	187	$77,231,000
Crash	3264	7.46%	243	$3,402,000
Total	4873	9.17%	447	$109,074,000

Number and value of casualty reductions elsewhere

These have been estimated by taking the number of crashes in each category prevented in Victoria and adjusting them for the number of registered vehicles and latitude applying to the other jurisdictions. The adjustment for number of vehicles consisted of multiplying the crashes prevented in Victoria by the term:

(Registered vehicles in Jurisdiction X/Registered vehicles in Victoria).

The adjustment for latitude consisted of multiplying the number of crashes prevented in Victoria by the term:

(Estimated reduction in Jurisdiction X/Estimated reduction in Victoria).

The value of the reductions was estimated by applying the BTE updated figures shown above.

The results are shown in Tables 4A to 7A.

Table 4A: Value of fatal crashes prevented

Jurisdiction	Adjustment for fleet size	Adjustment for latitude	Value of fatal crashes prevented
VIC	N/A	N/A	$28,441,000
NSW	1.13	0.82	$26,353,431
QLD	0.71	0.48	$9,692,693
WA	0.41	0.71	$8,279,175
SA	0.31	0.88	$7,758,705
TAS	0.10	1.42	$4,038,622
ACT	0.06	0.88	$1,501,685
NT	0.03	0.07	$59,726
Total	2.76	5.26	$86,125,036

Table 5A: Value of serious injury crashes prevented

Jurisdiction	Adjustment for fleet size	Adjustment for size of effect	Value of serious injury crashes prevented
VIC	N/A	N/A	$77,231,000
NSW	1.13	0.82	$71,562,245
QLD	0.71	0.48	$26,320,325
WA	0.41	0.71	$22,481,944
SA	0.31	0.88	$21,068,617
TAS	0.10	1.42	$10,966,802
ACT	0.06	0.88	$4,077,797
NT	0.03	0.07	$162,185
Total	2.76	5.26	$233,870,914

Table 6A: Value of other injury crashes prevented

Jurisdiction	Adjustment for fleet size	Adjustment for size of effect	Value of other injury crashes prevented
VIC	N/A	N/A	$3,402,000
NSW	1.13	0.82	$3,152,293
QLD	0.71	0.48	$1,159,402
WA	0.41	0.71	$990,322
SA	0.31	0.88	$928,066
TAS	0.10	1.42	$483,084
ACT	0.06	0.88	$179,626
NT	0.03	0.07	$7144
Total	2.76	5.26	$10,301,936

Table 7A: Value of DRL to individual vehicle operators

Jurisdiction	Upper value(UV)	Lower value(LV)	Number of vehicles	UV per vehicle	LV per vehicle
VIC	$109,074,000	$105,672,000	3,310,944	$32.94	$31.92
NSW	$101,067,968	$97,915,675	3,751,483	$26.94	$26.10
QLD	$37,172,419	$36,013,018	2,366,880	$15.71	$15.22
WA	$31,751,441	$30,761,119	1,359,145	$23.36	$22.63
SA	$29,755,387	$28,827,322	1,034,663	$28.76	$27.86
TAS	$15,488,508	$15,005,424	326,247	$47.47	$45.99
ACT	$5,759,107	$5,579,482	201,236	$28.62	$27.73
NT	$229,055	$221,911	100,381	$2.28	$2.21
Total	$330,297,887	$319,995,950	12,450,979	$206.08	$199.66

A5 Expected crash reduction benefits under specific models

Following the estimates of the crash savings in Section A4, it is assumed that only multiple-party crashes will be affected, and that the crash reductions estimated will occur only during dawn and dusk, and during periods of adverse weather.

The analysis of the VicRoads crash data from 1999-2002 indicated that only 15% of multiple-party daytime crashes occurred on wet roads. The data also show that 8% of the defined crashes occurred during dawn or dusk.

The specific crash reduction benefits which might be expected from each of these models is as follows.

Model 1 (ADR full time) and Model 2 (low beam): Since the lights operate all the time, these lights would be expected to deliver the full range of crash reductions estimated above. However, the evidence is that DRL have little if any effect, except during conditions of low ambient illumination. The crash reductions are therefore likely to be concentrated in the periods around dawn and dusk, and during adverse weather.

Model 3 (ADR sensor): Under Model 3, DRL will automatically be switched on when ambient light reaches a critical level. Provided an appropriate triggering point is set, Model 3 should capture all the benefits of Models 1 and 2.

Model 4 (limited low beam): Model 4 requires drivers to turn on their headlights in the periods before sunset, and to continue to use them in the period after sunrise. This would capture similar benefits to the other models in the pre-dusk and post-dawn periods, but not the benefits which result from headlight use during adverse weather. The benefits associated with this model have therefore been adjusted downwards. The Victorian CrashStats results show that 15.3% of target crashes occur on wet roads, and 8% occur during dusk or dawn.

Under Model 4, the crash reductions expected are the following proportion of crash reductions expected under the other models:

$$8.0/(15.3+ 8.0) = 0.34$$

A6 Benefit-cost analysis

A life of 15 years has been assumed for a new motor vehicle. Table 8A shows, for each model, the capital costs, and the running costs summed over the life of the vehicle, using a discount rate for future running costs of 7%. Crash savings have also been summed over the life of the vehicle, also discounted by 7%. The Net Present Value is calculated by subtracting running costs and capital costs from net benefits, and the benefit-cost ratio by dividing the net benefits by the sun of the running costs and capital costs.

All models have a positive NPV and a benefit-cost ratio greater than 1. However, the lowest NPVs and benefit-cost ratios are for the Models where the DRL are on all the time during daylight (Models 1A [ADR full time 100W], 1B [ADR full time 40W] and 2 [low beam]). Models where the DRL operate only when needed have higher NPVs and benefit-cost ratios, since costs are lower and it has been assumed they will capture all the benefits that the other models would. The savings in running costs for Models 3A (ADR sensor 100W) and 3B (ADR sensor 40W) compared to Models 1A (ADR full time 100W) and 1B (ADR full time 40W) suggest that it is worth investing in the light-activated sensor to control the lights.

Model 1A would be expected to deliver the full range of benefits, but has relatively high capital costs and running costs. It is fully automated, so there would be no problems with compliance or flat batteries from leaving lights on.

Model1B also delivers the full range of benefits but at lower capital and running costs than 1A. It would also deliver the full range of benefits, and is also fully automated.

Model 2 (low beam) involves no capital costs but relatively high running costs. It has been assumed it will deliver the full range of benefits, but there may be problems with compliance through people forgetting to turn on their lights, or choosing not to comply. In the French trial discussed in Section 4.2.5 (Lassarre, 2002), use rates in built-up areas remained low. It may also be anticipated there would be a problem with people forgetting to turn off their lights during the day when the vehicle was stopped. We have not attempted to make estimates in relation to these issues.

Model 3A (ADR sensor 100W) is assumed to deliver the full range of benefits in recognition of Cobb's findings that DRL improved conspicuity only under conditions of low ambient lighting (Cobb 2001, see Section 3.4). This may not be a realistic assumption. There may be situations on the road where full-time DRL do confer an advantage during normal daylight conditions. For example, DRL may have a role in alerting other road users when the vehicle is deep in shadow, particularly if that shadow is intermittent so that there is no opportunity for brightness adaptation to develop.

The extent to which Models 1A, 1B and 2 will deliver greater crash reductions than Models 3A or 3B will depend on how the sensor is set up. Two parameters are critical. The first is the triggering level for DRL in terms of ambient threshold levels. The second is the length of time for which the ambient light level has fallen below the triggering level before the sensor brings the lights on. With a high triggering level and short triggering period, the DRL would come on in a wide range of situations and safety benefits would be close to that of Models 1A, 1B and 2. With a lower triggering value and a longer triggering period, the DRL would come on less frequently and the safety benefits might be lower than with Models 1A, 1B and 2. More evidence is required on this point.

Under Model 3A and 3B, the system is fully automated, so problems with compliance and leaving lights on should be avoided.

Similar points apply to Model 3B (ADR sensor 40W), which has lower capital costs and running costs than does Model 3A.

It has been assumed that Model 4 (limited low beam) will prevent crashes only during the dawn and dusk periods. The benefits are therefore lower than those for other models, but there are low running costs and no capital costs, so the benefit-cost ratio is relatively high. Some means would have to be put into place to encourage compliance – perhaps radio announcements and reminders at the appropriate times would be sufficient to achieve reasonable compliance levels.

Table 8A: Benefit-cost analyses associated with the different DRL models

Model	Capital costs $	Lifetime running costs $	Lifetime benefits $	NPV $	Benefit/ Cost ratio
Model 1A (ADR full time 100W) 160 hrs operation	30.00	145.76	236.86	61.10	1.35
Model 1B (ADR full time 40W) 160 hrs operation	4.00	112.96	236.86	119.90	2.03
Model 2 (low beam 200W) 160 hrs operation	0.00	200.42	236.86	36.44	1.18
Model 3A (ADR sensor 100W) 37 hrs operation	50.00	34.62	236.86	152.24	2.80
Model 3B (ADR sensor 40W) 37 hrs operation	24.00	27.79	236.86	185.07	4.59
Model 4 (limited low beam 200W) 13 hrs operation	0.00	23.32	80.62	57.39	3.47