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FUNCTIONAL REQUIREMENTS FOR DAYTIME RUNNING LIGHTS

Kåre Rumar

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16. Abstract

Late detection is the basic mechanism responsible for daytime collisions. One goal of this report is to review evidence concerning the effectiveness of daytime running lights (DRLs) to increase vehicle conspicuity, and thereby facilitate vehicle detection and reduce the number of daytime collisions (including collisions between cars and unprotected road users). Another goal is to recommend lighting characteristics of dedicated DRLs.

The available accident studies indicate that DRLs are effective in reducing the number of daytime collisions. Furthermore, this reduction is larger for pedestrians and cyclists than for motor vehicles.

Evidence indicates that the minimum intensity of DRLs should be about 400 cd. Although increased intensity of DRLs results in increased effectiveness, it also results in increased glare. Consequently, an upper limit on the intensity of DRLs is justified. Arguments are presented that for the relevant levels of ambient illumination (1,500 – 40,000 lux), the maximum intensity for dedicated DRLs should be about 1,500 cd. The report also discusses recommended DRL light distributions, non-dedicated DRL alternatives, and the use of rear lamps with DRLs.

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1. EARLY EXPERIENCES

In this report the term DRLs (Daytime Running Lights) is used in a very general sense. DRLs refers to any lamps on the front of the vehicle (mainly low beams and dedicated DRLs) that are intended to burn during daylight conditions to enhance vehicle conspicuity. DRLs should be considered as a marking light, marking vehicle presence.

Turning vehicle lights on during the daytime originated in the USA in the early 1960s. The initial purpose was probably not to improve road safety, but to act as a sort of symbol to represent a safe company fleet or safe driving in general. In some cases, it also served to remind drivers in that fleet and other road users that the fleet was running a safety campaign including many activities. The idea that DRLs could be a safety measure in their own right probably originated in Texas in 1961 as the safety campaign "See the lights" (Allen and Clark, 1964). It was immediately taken up by several organizations, among them the American Trucking Association (Nichols, 1961). The most well known of all early fleets using DRL–the Greyhound bus company–did so for a combination of both reasons (as a safety symbol and safety measure). The company had initiated a number of actions to improve the safety of the fleet, and the DRLs served both as reminders of this campaign and as one of the safety measures.

But the opposition to DRLs as a safety measure was strong. In fact, as Allen and Clark (1965) point out, investigators at that time remarked, "It seems that no one can conceive of an automobile or a Greyhound bus being invisible on a bright clear day." That opinion is also somewhat representative of the present situation and it is a considerable problem, primarily for decision makers. That is probably also the reason why so few of the early DRL efforts were studied systematically; few believed that DRLs would have any direct safety effect.

More anecdotally, the author was driving in the Soviet Union in 1966 and using DRLs (low beams) during daylight, in line with recently carried out research and Swedish recommendations. On one occasion I was stopped and fined 5 rubels because turning on headlights during daylight was reserved for Soviet army vehicles. That made sense because the army vehicles were painted in camouflage colors and therefore had a comparatively low conspicuity.

Most of the DRL efforts reported above were using standard low beams as DRLs. The concept of DRLs as symbols is illustrated by the fact that a newspaper, the Indianapolis Star, promoted the use of a single, centrally positioned 21-cd light as a DRL. A document from the

American Automobile Association (1965) refers to DRLs as one or two 21-cd lamps on the front of the vehicle, and also states that the primary purpose of DRLs is to remind drivers to be careful. Increased attention and visibility were considered secondary. (The 21-cd luminous intensity is much too low if the purpose is to increase peripheral vehicle conspicuity during daylight.)

2. BASIC CONCEPT AND PERCEPTUAL THEORY

According to Rumar (1990), the basic driver error is late detection. A large majority (75 to 85%) of the road crashes causing human injury are collisions between road users (UN, 2001). About 50% of all vehicle crashes are daytime collisions (Bergkvist, 2001) and the purpose of DRLs is to reduce these daytime collisions. Treat (1977) and Sabey and Staughton (1975) used an in-depth accident methodology to show that the dominant driver error in crashes are perceptual errors such as detection and recognition. The most frequent explanation for the collision that road users give is of the type "I saw him too late to ….".

Rumar divides the failure to detect the other road user in time into two categories:

- A cognitive error, illustrated by a failure to look in the correct direction or a failure to look for the specific road user in question. We may call this a lapse of cognitive expectation.
- A perceptual error, illustrated by a failure to detect another road user in peripheral vision or in lower levels of ambient illumination. We may call this a visual threshold difficulty.

Engel (1976) and Hughes and Cole (1984) make similar distinctions. Engel distinguishes between what he calls cognitive conspicuity and visual conspicuity, and Hughes and Cole distinguish between what they call search conspicuity and attention conspicuity. In other words, conspicuity is not only an effect of the physical properties of the target but also an effect of the observer characteristics. If we have the correct expectation of where relevant targets will appear, our capacity to detect targets is very high even if the conspicuity characteristics of the target are very weak. In such situations, the probability that we will detect the target too late is very low. However, if we do not have the correct expectation of target position, the conspicuity characteristics of the relevant target must be very strong. Otherwise it is likely that we will detect the target too late.

If we transform this discussion to the real road traffic situation, we may say that if another road user appears where we expect him to appear, we normally detect him in time even if he is not particularly conspicuous. Thereby potential incidents and collisions may be avoided. However, if a road user appears from an unexpected direction (in the periphery of the eye) his conspicuity must be very strong for us to detect him in time to avoid a collision.

Now why would we need artificially increased conspicuity of large objects like cars, buses, and trucks when in the history of man we have been able to detect much smaller prey and enemies well enough to successfully survive for such a long time on earth? The simple answer is probably that our prey and enemies in the past had a characteristic that present motor vehicles lack–motion! (The periphery of our eyes is very sensitive to motion.) So even if we did not look in the relevant direction we were warned about the presence of enemies by the motion in the periphery of our eyes. However, automobiles have no intrinsic motion when they come against us even at high speed. We cannot see the motion of the wheels, and the image of the car on the retina increases so slowly that it is often below the threshold for detecting motion.

What we are trying to say is that our ecologically developed perceptual systems do not work perfectly in the new situation represented by road traffic. When vehicles appear where we expect them to appear, we detect them without any real problems. When vehicles appear where we do not expect them to appear, we look in other directions. Therefore, the conspicuity of vehicles needs to be enhanced, especially in the peripheral visual field.

What alternatives to DRLs could enhance vehicle conspicuity in daylight? One possibility could be vehicle color. Allen and Clark (1965) used 21 cd DRLs on cars with different brightness and made some preliminary observations. Many of their results were later confirmed by Dahlstedt and Rumar (1973) and Rumar (1980) in more systematic investigations on the effect of vehicle color and low beam DRLs on conspicuity. Their investigation was initiated by a study by Viberg (1966), who reported striking differences between proportion in traffic and proportion in accidents of cars with different colors. Viberg's results indicated that cars with bright and saturated colors were underrepresented in crashes while cars with dark and unsaturated colors were over-represented in crashes, in relation to their frequency in normal traffic.

Two different approaches were used by Dahlstedt and Rumar (1973) and Rumar (1980). First a pilot test in real traffic was carried out. Subjects driving on rural roads were asked to make verbal reports stating what caused them to detect oncoming cars. At the same time a photo was taken. The results showed that color was very rarely the reason for detection. Luminance contrast was the most common cause for detection, followed by reflections in the windscreen, the chromium parts, or the paint. But the most striking result was that as soon as the oncoming car had its lights on (low beams), that became the reason for detection. Then an experimental study with photos of simulated cars with different colors against various backgrounds (forest, field, road, etc.) was carried out. The detection time of the subjects was measured. The results showed that colors, which are very conspicuous against one background, might be less noticeable against another background and vice versa. And again, headlights on proved to give the shortest reaction times (highest conspicuity), despite the fact that a picture of a light source has a much lower intensity than the light source itself. Rumar (1974) reached the same conclusions in an experiment using tachistoscopic exposure of pictures of cars in different colors with and without low beams. Rumar (1976) discusses the question of vehicle color and low beams in more detail and comes to the same conclusion. The color of a car is not an alternative to DRLs as a general conspicuity-enhancement measure. DRLs are superior or equal to the best color against any background.

From this analysis it follows that the primary purpose of DRLs is to enhance vehicle conspicuity, to compensate for the expectation errors of drivers and for the lack of perceived motion of motor vehicles. Thus, DRLs are designed to increase visual conspicuity or search conspicuity of vehicles in order to compensate for lack of cognitive conspicuity or attention conspicuity.

3. DRL PURPOSE AND PROBLEM ANALYSIS

As stated at the end of Section 2, the primary purpose of DRLs is to enhance motor vehicle conspicuity in daylight conditions. In this section, we discuss in which conditions and situations DRLs are supposed to function, potential advantages of DRLs other than improved vehicle conspicuity, and potential disadvantages that DRLs may introduce. These questions will be treated more in depth when results of various studies are summarized and analyzed in the following sections.

3.1. General conditions in which DRLs should work

DRLs should be intended only for daylight conditions. At lower levels of daylight illumination and in street-lighted areas, standard automobile lighting must be used. In severely reduced visibility due to adverse weather conditions (e.g., in heavy fog) standard low beams or even fog lamps or high beams should be used. It is difficult to specify any specific limit between these two conditions. The SAE Recommended Practice for DRLs (SAE, 1997) specifies that if a sensor is used to switch DRLs on and off, it shall be set at 1,000 lux in the upward direction (sky illumination). That seems to be a reasonable, although somewhat low, limit. Another way to describe the limit is to say that when the driver needs dashboard illumination to see the instruments, then standard headlamps, and not DRLs, should be used. That way of specifying the borderline works well when visibility is reduced due to lower illumination, but does not work in adverse weather. In the future it may be expected that some semi-intelligent sensors will determine the borderline between the usage of DRLs and standard headlamps.

Furthermore, DRLs are expected to work both in rural and urban conditions, during summer and during winter, and on straight roads, in vertical and horizontal curves, and at intersections. Not only drivers of vehicles (including buses and trucks), but also drivers of motorcycles, mopeds, and bicycles are expected to benefit from DRLs. And finally, DRLs must also improve the situation for pedestrians. These unprotected road users have a considerably higher road traffic risk than occupants of vehicles. This difference should preferably decrease as an effect of DRLs.

DRLs are expected to enhance vehicle conspicuity at long viewing distances (e.g., overtaking situations with oncoming cars on rural roads) as well as at short distances (e.g., pedestrian crossings and intersections in urban settings). The primary conspicuity interest is in the forward direction because if the vehicle is not directed towards you, it is not of immediate danger or interest. (An exception may be at intersections where a vehicle might be on a collision course although it initially is at a rather large peripheral angle).

3.2. Potential advantages of DRLs other than enhanced conspicuity

As has been stated above, the primary purpose of DRLs is to enhance vehicle conspicuity especially in the peripheral visual field of other road users. But there are other situations in which DRLs are expected to be of benefit. The following advantages have been pointed out by past research (Helmers, 1988; CIE, 1993; Koornstra et al., 1997; White, 1998):

- *Distance estimation*. Based on general perceptual knowledge and several studies it is expected that cars equipped with DRLs, which have increasing stimulus intensity and contrast, will be perceived as being closer than non-equipped cars. This would be favorable from a road safety point of view in situations such as overtaking and gap acceptance.
- *Vehicle position*. Studies indicate that a DRL-equipped vehicle (having a higher contrast with the background) would be easier to position laterally on the roadway.
- *Motion*. If DRLs would be on only when the engine is running, it would facilitate the perceptual discrimination between active cars (possibly moving) and inactive or parked cars.
- *Speed*. Will the combined effect of these potential advantages result in more accurate or safer estimation of speed?
- *Vehicle identification*. Could DRLs work as a means to identify a vehicle category?
- *Back-up*. Regulations require lights to be on during temporary low visibility conditions (e.g., fog patches, tunnels, etc.). However, there is an obvious risk that drivers in such situations would forget to turn on their lights. DRLs would eliminate that risk.

3.3. Potential risks following an introduction of DRLs

A number of potentially adverse effects have been mentioned in the literature (Helmers, 1988; CIE, 1993; Koornstra et al., 1997; White, 1998; GRE, 2003a). The most frequently-mentioned potential risk with DRLs is their masking effect. Here are the most frequently mentioned potential risks:

- *Novelty*. No effect if all cars have DRL.
- *Masking*.
  - Impaired conspicuity for cars without DRLs.
  - Impaired conspicuity for other road users (cyclists, pedestrians) if all motor vehicles have DRLs.
  - Impaired conspicuity for motorcycles with DRLs if all cars also have DRLs.
  - Impaired visibility of signal lights, such as turn signals and brake lights.
- *Glare*. DRLs may cause glare depending on the relation between DRL intensity and level of ambient illumination.
- *Compensatory reactions*. Drivers may respond to a subjective feeling of increased safety due to DRLs with more reckless behavior (e.g., increased speed).
- *Costs and safety*. Increased costs and "one-eyed" vehicles due to wearing out of light sources.
- *Costs and environment*. Increased fuel consumption and pollution.
- *Durability*. Special DRLs that are not integrated in the standard front lighting system may quickly lose their efficiency due to dirt, corrosion, etc.

4. METHODOLOGICAL PROBLEMS

Applied studies in general, and road safety studies in particular, are difficult from a methodological point of view. In order to generalize from specific study results, certain minimum limits of reliability (accuracy and repeatability) and validity (truthfulness in that it represents reality) need to be met.

There are two main types of studies on DRLs in the literature. One type deals with the problems related to perceptual effects of DRLs. The other type of studies deals with the general effects of DRLs (accident, environment, and cost). These later studies are mainly statistical, but some are technical or financial. Both types will now be briefly discussed in the context of methodological issues.

4.1. Perceptual studies

The perceptual studies on DRLs may be divided into conspicuity studies, estimation studies (distance, position, speed), and identification studies (vehicle category). All have reliability problems because of normal human variation. But that is normal for behavioral studies. A more difficult problem is the validity of the conspicuity studies. Conspicuity is related to attention, and attention is a very sensitive topic. If the subjects know that their attention is studied, their performance is normally much better than for completely naïve subjects (Roper and Howard, 1938). However, even if the absolute results (e.g., in meters, angles, or candela) cannot be fully trusted (generalized to real situations), the relative results (the ranking between situations) should be correct, even in alerted situations. Hagenzieker (1990) argues that most of the perceptual studies carried out so far are not realistic enough, by, for example, lacking any cognitive load.

Not until recently (Thompson, 2003) has the number of cars equipped with various types of DRLs been large enough to permit scientifically sound analyses based on accident statistics of the effects of various types of DRLs. Therefore, perceptual studies, which offer reliable results, have thus far been the basis for defining the functional requirements for DRLs.

The numbers of cars equipped with various types of DRLs are probably not large enough, and not described in enough detail (type and characteristics of DRLs), to be used in an accident analysis with the purpose of finding different effects between DRL characteristics. Therefore, perceptual studies, which at least offer reliable relative results, should probably be the main basis for deciding the functional requirements of DRLs.

4.2. Accident, environmental, and cost studies

Accident, environmental, and cost studies also have specific methodological problems. The main reliability problem with the statistical investigations of accidents is the considerable variation of accident data, which makes it difficult to reach significant results. Another problem involves the appropriate control conditions in comparing accidents with and without DRLs. Whether this comparison is of the before and after type, or using control groups or control areas, there are considerable problems proving that the control situation is fully identical in all respects to the experimental situation. If it is not, the results are questionable. Many of the reported DRL accident statistical studies suffer from this validity problem.

A special methodological problem is estimating the crash reduction effect of DRLs considering that in most of the studies a certain proportion of the cars were also equipped with DRLs even in the control conditions.

Accident statistical studies should be the main basis for deciding whether DRLs are worth introducing or even requiring. However, Thompson (2003) has recently shown that statistical studies could also be used for analyzing functional requirements.

The environmental and cost studies depend very much on driver behavior. And as with attention, behavior changes when subjects know they are being studied. In addition, many of these studies are simulations; that is to say, the behavioral component is not present but represented by a model. For instance, fuel consumption and pollution with and without DRLs may be technically very accurately calculated. But the realistic driving behavior and vehicle owner maintenance, none of which is near optimum, may in real life mask and reduce much of the potential difference shown in a theoretical comparison.

4.3. Compensatory behavior

Compensatory behavior is a problem that faces all road safety measures. When safety is improved by some measure, there is a substantial probability that the road users will adapt their behavior to the new situation and use the new situation to also gain things other than safety (e.g., speed). In the most extreme cases, all of the expected safety benefit is lost, which is called risk homeostasis (Wilde, 1982). However, in most cases there is only a reduction from the expected safety (Rumar and Berggrund, 1976). Elvik (1993) and Perel (1991) discuss the possibility of compensatory behavior with DRLs.

The key question is when behavioral adaptation occurs. What is required to trigger compensatory reactions? According to Rumar and Berggrund (1976), the key condition is the existence of feedback. If drivers feel that they have a higher level of safety (as for instance with seat belts, better road holding, better brakes, better road visibility, or an anti-collision system), then the probability of a compensatory behavior (e.g., increased speed) is high. However, if drivers do not feel that they have a higher level of safety, the risk of compensatory behavior is very low. Our interpretation is that DRLs do not give that feedback; drivers do not feel safer because they have lights on (especially if they are automatic). Therefore the probability that DRLs will create compensatory behavior is very low.

5. GENERAL CONDITIONS

In this section the results of various general DRL studies are reported and discussed. To some extent an overlap will be found between the studies reported in this and the following sections. However, it may facilitate reading and understanding the DRL problems and effects if the report is based on the questions instead of on the various available studies.

5.1. Ambient illumination level and latitude

In Section 3 it was stated that DRLs should be intended for daylight conditions and reasonable clear sight. DRLs should not be expected to work in lower levels of dawn and dusk illumination, or in severely reduced sight conditions. However, this does not specify at what range of ambient illumination DRLs should be expected to improve vehicle conspicuity. And as many studies show, there is a clear relation between level of ambient illumination and the optimal luminous intensity of the DRL. If DRLs should effectively enhance vehicle conspicuity in the periphery in very bright sunshine, they must be much more intense than if the enhancement is expected to take place in moderate or lower levels of daylight illumination (Attwood, 1975, 1981; Hörberg and Rumar, 1979; Rumar, 1981; SAE, 1985; Kirkpatrick et al., 1987; Padmos, 1988; Ziedman and Burger, 1993). It is therefore not surprising that the voluntary usage of DRLs (low beams) increases with reduced ambient illumination (Andersson and Nilsson, 1981; Lindeijer and Bijleveld, 1990; Lindeijer and Bijleveld, 1991; Hocherman and Hakkert, 1991).

The limiting factor concerning suitable intensity of DRLs in high levels of daylight illumination is glare, that DRL light intensity might create in lower levels of daylight illumination. This question is discussed in Sections 6.8 and 9.3.2.

General ambient illumination and duration of the twilight periods are related to latitude of the area. In December, the level of the daylight illumination in the middle of the day is about five times higher at 40º North (Washington, San Francisco, Rome, Madrid) than at 60º North (Helsinki, Oslo, Stockholm). In June, the duration of the twilight periods at 40º North is about 65 minutes while at 60º North the periods are about 215 minutes (NTR, 1976).

Koornstra et al. (1997) have analyzed accident statistics studies of DRLs from 12 countries in different latitudes. In their analysis, they have tried to describe the effect of DRLs as compared to no DRLs. In other words, there is normally a certain usage of DRLs even before legislation is introduced, but they have tried to compensate for this by taking into account the usage level of DRLs when the studies start and end. Their predictions of the total (intrinsic) DRL effect on accidents as a function of latitude is shown in Figure 1.

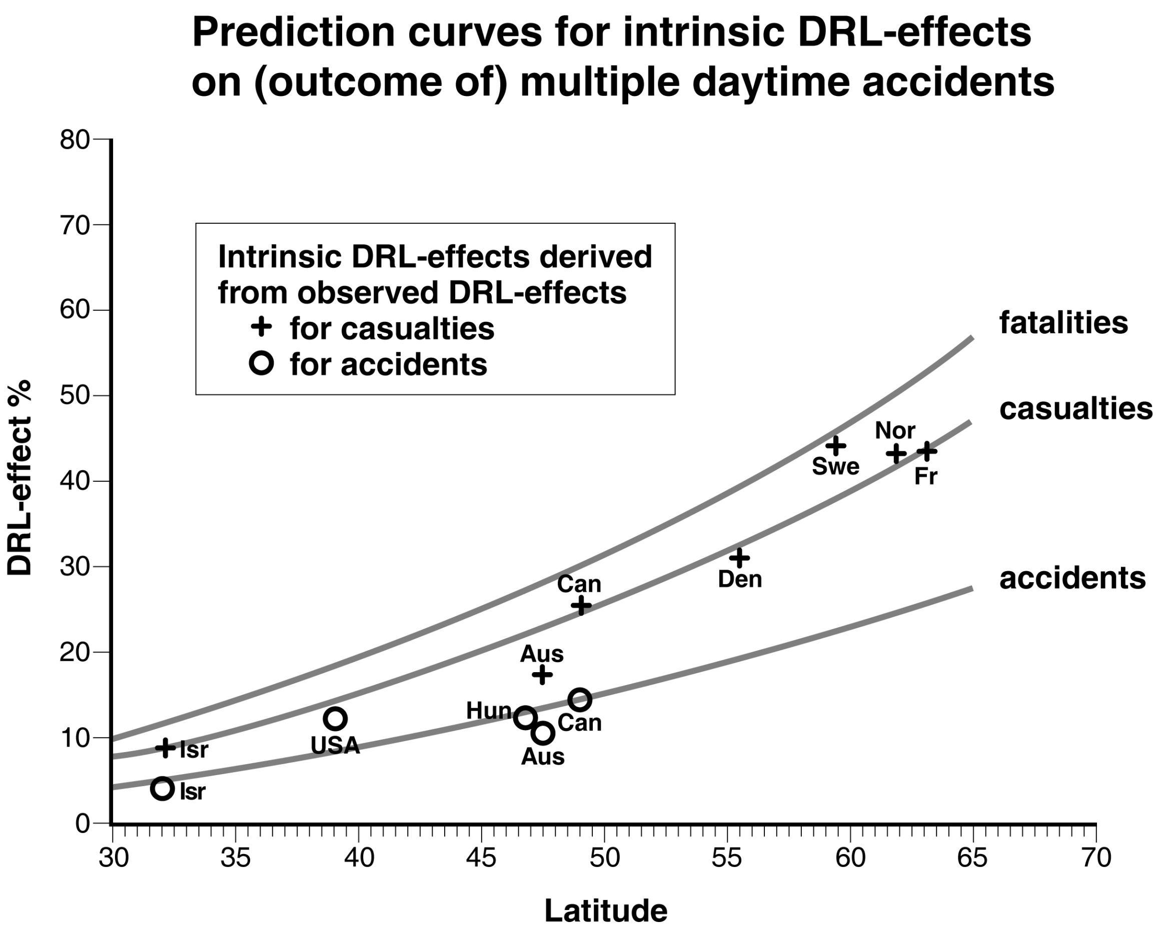

Figure 1. Prediction curves for intrinsic DRL-effects (from no usage to 100% usage) on multiple daytime accidents. (from Koornstra et al., 1997)

5.2. Weather conditions

It is often argued that compulsory DRLs would make certain that drivers use adequate lights in temporary conditions when lights should be on, but are often forgotten, such as fog patches, smoke or whirling snow, short tunnels, etc. Rumar (1975) observed the usage of low beams in Sweden as a function of ambient illumination. He found that at an ambient illumination level of 100 lux, more than 90% of the vehicles had low beams on. But at an ambient illumination level of 1,000 lux, only just over 50% of the cars had low beams on. Sävenhed (1977) studied the Swedish situation in 1975/76 and found that in poor illumination conditions, 90% had low beams or special DRLs on while in good illumination conditions, only 50% had lights on. Johnson (1990) has made corresponding studies in the USA. He observed how many drivers forget or neglect to turn on their lights in situations that call for lights. This back-up effect of DRLs could be considered a secondary advantage of DRLs. It should be noted, however, that in order to work well in very bad visibility conditions, the other marking lights (primarily rear lights) should be on as well. No special studies of DRL effects or performance in adverse weather conditions have been found, but Rumar (1974) mentions that the effect of DRLs (low beams) was especially strong in slight haze.

Another problem may appear in bad weather conditions if marking lights are not on together with DRLs. DRLs will enhance the vehicle's frontal conspicuity, but may cause the vehicle rear and side conspicuity to be reduced, compared to the vehicle having low beams and marking lights on together.

5.3. Urban/rural conditions

As mentioned in Section 3, DRLs are expected to work both in rural and in urban situations. Most perceptual studies are, however, carried out in rural situations, though several statistical studies do include urban situations. Several of these studies (Andersson and Nilsson, 1981; Lindeijer and Bijleveld, 1991; Hocherman and Hakkert, 1991) show that the voluntary use of DRLs tends to be lower in urban areas than in rural areas. This may be contrasted with the accident analysis results, which show that the crash reduction with DRLs tends to be greater in urban areas (Andersson and Nilsson, 1981). This may have to do with the large proportion of unprotected road users in urban areas (see Section 5.4 below).

5.4. Pedestrians and cyclists

In Section 3 it was stated that DRLs are expected to provide at least as many benefits to unprotected road users (cyclists, pedestrians) as to car occupants and motorcyclists, because they have higher accident and injury risks.

Koornstra et al. (1997) argue that the effect of DRLs in urban areas might be stronger than in rural areas because there are a larger proportion of road users with low speed. Those road users (pedestrians and to some extent cyclists) are able to stop, or respond in other ways, when they suddenly detect an oncoming car. Cars, on the other hand, especially in rural areas, often have higher speeds and require longer reaction and maneuvering distances after detection of other road users. Another explanation could be that unprotected road users more often have a need to detect an oncoming vehicle in the peripheral visual field. A third explanation could be that the proportion of older persons is higher in the category of unprotected road users, and older persons have a more reduced functional visual field and greater difficulties turning their head. In any case, the results by Andersson and Nilsson (1981), NHTSA (2000), Bergkvist (2001), and Thompson (2003) seem to verify that the DRL effect for unprotected road users is substantially greater than for cars. They report the largest crash reductions for pedestrians and cyclists in urban areas.

The special problems of motorcycles are treated in Section 6.10.

5.5. Legislation

The DRL story started as a symbol for road safety, a sign that drivers should or do follow the safety rules (see Section 1). For instance, in Sweden DRLs were used also as a sign and reminder in connection with the changeover from left to right hand traffic in 1967. However it was soon realized that while conspicuity was enhanced for DRL-equipped vehicles, the conspicuity of non-equipped vehicles might suffer. Attwood (1977, 1979) showed that such masking did occur and that the effect was stronger the lower the level of ambient illumination and the stronger the intensity of the DRLs. Hole and Tyrell (1995) obtained similar results in their studies of motorcycle DRLs. Therefore a discussion of legislation requiring compulsory DRLs on all motor vehicles (and an upper limit of DRL intensity) started. (Motorcycles constitute a special problem in this respect and are treated in Section 6.10 below.)

The first countries to legislate compulsory DRLs for motor vehicles were Finland and Sweden in 1977. (Finland already had a partial law for DRLs, during the half year of winter in rural areas since 1972.) Norway followed in 1985 with DRLs on all new cars (and then on all cars in 1988), Iceland in 1988, and Denmark in 1990. Canada introduced compulsory DRLs for all new cars in 1989, and Hungary did so in 1993. In 2002, Italy began requiring lights on during the daytime for motorized two-wheelers on all roads, and for cars on motorways and main roads. This new requirement is expected to be extended to all roads outside of built up areas (GRE, 2003b). In Switzerland, DRLs have been recommended since 2002. Poland required low beams to be on during the four winter months since 1991 (Wronski, 1993). In 1996 Poland extended its DRL requirement to five months of winter (Przybylski, 1996). GM (2001) petitioned NHTSA to require DRLs on cars in the USA, but NHTSA has not yet responded. Plans and campaigns have been carried out in USA, EU, Netherlands, Austria, Australia, Germany, Lithuania, and other countries. In all these actions, recommendations, and legislations, standard low beams have been accepted as DRLs. In some countries, other embodiments (such as modified low beams, reduced-intensity high beams, turn signals, fog lamps) are also allowed.

5.6. Public attitude

As was noted earlier, public opinion about DRLs before they are introduced (and become commonplace) is a difficult issue. The oversimplified but not uncommon argument against DRLs is roughly, “If you cannot see a bus in full daylight, you should not have a driver’s license!” However, after the introduction of DRLs, the public attitude seems to change. For instance, in Sweden where DRLs have been compulsory since 1977, only a small minority would now like to have the legislation repealed. Unprotected road users and older persons are especially positive about DRLs. However, there is a lesson to learn from these initially negative attitudes: Before DRLs are promoted and legislated, a wide and intensive educational campaign should be carried out. If this is not done, there is a clear risk of backlash.

Before the Swedish requirement of DRLs, studies were made to investigate which drivers used DRLs and which did not. At that time (1975), the general usage during full daylight was about 15%. The results showed (Engdahl, 1976) that young drivers, frequent drivers, rural drivers, and safety-minded drivers followed the DRL recommendation better than the others. The arguments for not having the lights on included “no need in broad daylight; I can see anyway; easy to forget they’re on when you leave the car; I do not want to burn my bulbs”.

Motorcyclists are a special road user group opposed to general DRL legislation for all motor vehicles. Their specific views and problems are treated below in Section 6.10.

5.7. Existing regulations and requirements (standards)

The UN Regulation (ECE-R87) specifies the lighting characteristics of dedicated DRLs (ECE, 1993). Efforts are presently in progress to amend this regulation (GTB, 2003). The current regulation specifies a minimum intensity of 400 cd at the optical axis and a maximum intensity in any direction of 800 cd. The color should be white. In SAE Recommended Practice J2087 (SAE, 1997) the minimum at the optical axis is given as 400 cd (“Photometric Requirements”) or 500 cd (“Photometric Design Guidelines”), and the maximum is 7,000 cd. In U.S. Federal Motor Vehicle Safety Standard 108 (FMVSS, 2002) the minimum at the optical axis is 500 cd. The maximum at any location in the beam is 3,000 cd unless headlamps are used for the DRL function. For low beams used as DRLs, there is no maximum specific to the DRL function. If high beams are used as DRLs, the maximum at the optical axis is 7,000 cd (and the centers of the lamps must be no higher than 864 mm from the ground). Fog lamps and parking lamps are not allowed as DRLs by FMVSS 108. In both SAE J2087 and FMVSS 108 the color of DRLs can be white, white to yellow, white to selective yellow,. selective yellow, or yellow.

In Canada (White, 1998; CMVSS, 2001; Rice, 2003), the DRL requirements (CMVSS 108) generally correspond to the SAE. However, there are differences. Lamps, except low and high beams, are required to have intensities between 500 cd (centrally) and 3,000 cd, with at least 250 cd at H-10L & R. There is no minimum required lamp area. Fog lamps are allowed as DRLs. The intensity of reduced low beams is specified in detail depending on the type of headlamp. Reduced-intensity high beams should have a central intensity of 2,000 cd to 7,000 cd (low and high beams could be combined to meet that requirement). DRLs should be as far separated as possible, and mounted 380 mm to 2,110 mm above the ground. The switching, both on and off, should be automatic. If there is a telltale to indicate to the driver that the marker lamps are switched off, marker lamps must not be on together with DRLs. Figure 2 compares the light distributions of the two main existing sets of requirements (ECE-R87, SAE J2087) for dedicated DRLs.

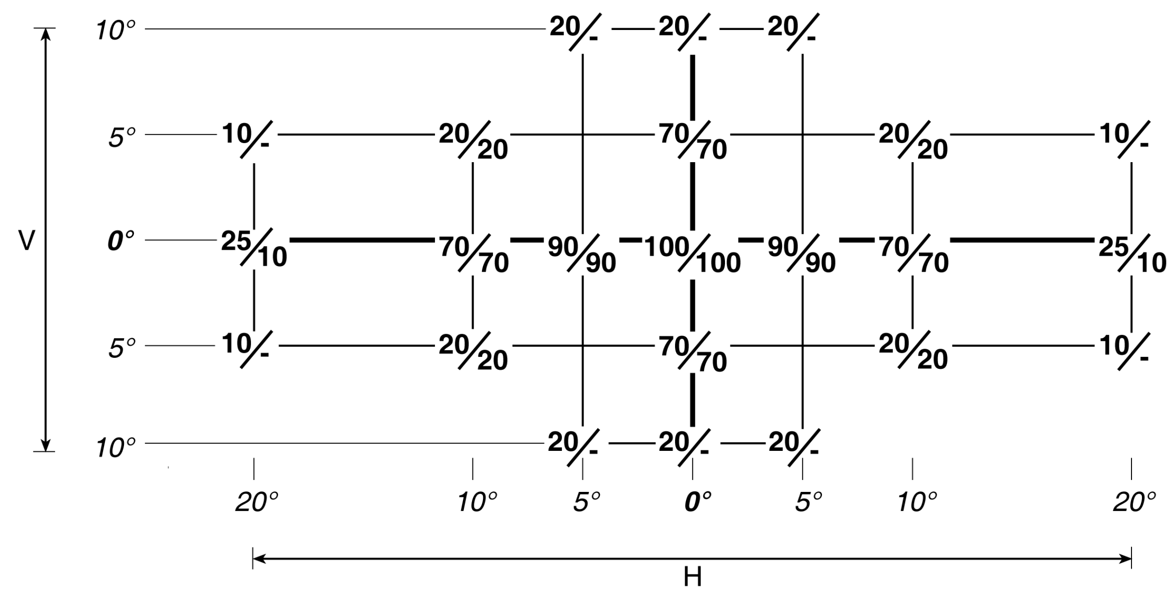

Figure 2. The required minimum intensities at various test points for DRLs according to ECE and SAE (as percentages of the minimum intensity required at HV). The values at each point are given as ECE/SAE.

6. PERCEPTUAL AND TECHNICAL ISSUES

This section summarizes results from studies covering several visual and technical issues.

6.1. Novelty effect

The idea that the positive conspicuity effect of DRLs would disappear if all vehicles had them is often mentioned by critics of DRLs. They believe that people would adapt to DRLs to such an extent that they would no longer notice them (behavioral adaptation). This effect has not been directly studied. But Hollo (1998) shows in his study of DRLs in Hungary that the related accident reduction is not a mere novelty effect. And it is our belief that DRLs rely on a basic visual function–contrast sensitivity–and therefore will not be influenced by behavioral adaptation. A novelty effect would have a larger cognitive component, which DRLs do not have.

6.2. Peripheral conspicuity

In rural conditions, the relevant peripheral angles (as seen from the vehicle) in which DRLs should be effective are probably comparatively small (less than 10º horizontally), except for intersections. In urban situations on the other hand, the relevant peripheral angles are often quite large (more than 10º horizontally), especially for unprotected road users. The relevant vertical periphery is relatively negligible (less than 5º vertically). The 5º vertical angle upward is based on, for example, the angle from the DRLs to a pedestrian at a distance of 15 m, or from the DRLs to a truck driver at a distance of 30 m. The 5º angle downward is based on situations like hillcrests. In most traffic situations (except intersections), the car is coming straight towards the observer, and the central part of the DRL light distribution is the most important part.

Hörberg and Rumar (1975) studied detection distance at 30º and 60º peripheral observation angles for vehicles without DRLs and with DRLs varying from 50 cd to 60,000 cd. They also studied detection distances in similar experiments at lower levels of ambient illumination (3,000 to 6,000 lux) at a 20º peripheral angle. Kirkpatrick et al. (1987) repeated a corresponding investigation with a 15º peripheral angle but at much higher ambient illumination levels (about 40,000 lux). Perel (1991) and Ziedman et al. (1990) used a 20º peripheral angle.

The various results of these studies are generally consistent. The higher the level of ambient illumination, or the larger the peripheral angle, the higher DRL intensity is needed to enhance vehicle conspicuity. For example, at very low levels of ambient illumination (less than 1,000 lux) and a peripheral angle of 20º, DRLs of 200 to 300 cd are enough to significantly increase detection distance. At moderate levels of ambient sky illumination (3,000 to 6,000 lux) and at a 30º peripheral angle, 400 cd DRLs roughly doubled the detection distance compared to no DRLs. At the same ambient illumination level, but at a 60º peripheral angle, DRLs of 400 cd had no effect, but DRLs of 60,000 cd increased the detection distance fourfold (Hörberg and Rumar, 1975). At higher levels of ambient sky illumination (50,000 to 70,000 lux) and at peripheral angles of 15 to 20º, DRLs with more than 2,000 cd were needed to significantly increase detection distance (Kirkpatrick et al., 1987; Ziedman et al., 1990; Perel, 1991; Ziedman and Burger, 1993). At extremely high ambient illumination levels (90,000 lux), DRLs of 600 cd were hardly noticeable, but DRLs of 5,000 cd were effective without producing glare (SAE, 1990).

Please note that moderate levels of DRL intensity (e.g., 800 cd) are not completely useless even on very bright days (e.g., 70,000 lux); there are always shadows from buildings, trees, mountains, etc, in which cars lose their normal conspicuity. In very bright sunshine, shadows are very dark and anything in the shadow is difficult to detect. Swedish pilot studies (unpublished) have shown that DRLs in such situations are quite effective in enhancing vehicle conspicuity.

In the future, DRLs could be semi-intelligent and able to adapt to the actual ambient illumination level (Rumar, 1997). It will then not be necessary to specify a specific range of luminous intensity; rather the DRL intensity will vary with the prevailing conditions.

6.3. Central conspicuity

Conspicuity of DRLs in the central vision is difficult to measure in detection terms because everything is detected at extremely long distances. Therefore, the few studies on central conspicuity of DRLs have often used the method of subjective estimation. Rumar (1974) used a tachistoscopic methodology with very short exposure times. Hörberg and Rumar (1975) used latency time to decide which of two cars in central vision was more conspicuous. The results showed that at moderate levels of ambient illumination (2,500 to 4,000 lux), even DRLs of 50 cd enhanced vehicle conspicuity. But DRLs of 400 cd were much more conspicuous.

6.4. Distance estimation

Dahlstedt and Rumar (1973) observed that vehicles with bright colors or with headlights on were estimated to be closer to the observer. Hörberg (1977) found that the more intense the DRLs, the closer the car was estimated to be. Cars without DRLs were estimated to be farthest away. The amount of the underestimation was 5 to 10%. Attwood (1976) obtained similar results.

Attwood (1976, 1981) studied gap acceptance in an overtaking situation with an oncoming car (with or without DRLs). He found that the more intense the DRLs and the lower the general ambient illumination level, the larger the minimum accepted gap. The effect with low beams and low ambient illumination (about 1000 lux) was considerable—(about 70 m) longer than without lights.

We are not aware of any studies on the effect of car DRLs on gap acceptance at intersection crossings. However, Olson et al. (1979) and Rabideau and Young (1979) carried out studies on the effect of motorcycle DRLs in such situations. The results indicate that the main effect of motorcycle DRLs was a larger variation of distance estimations. But there are considerable differences between motorcycle DRLs and automobile DRLs (see Section 6.10. below), and the results cannot necessarily be generalized to car situations.

6.5. Speed

No studies have been carried out on speed estimation of vehicles with and without DRLs. Howells et al. (1980) performed a study of the effects of DRLs on speed estimation of motorcycles. The results showed that the speed of motorcycles is generally underestimated. But no difference was found between motorcycles with and without DRLs. However, these results cannot immediately be generalized to cars, which have two DRLs and a larger front surface area, with both conditions related to more accurate distance and speed estimations.

6.6. Position, identification, and masking of other road users

Attwood (1976) found that it is easier to estimate the lateral position on the road of vehicles equipped with DRLs than those without DRLs.

Cobb (1992) studied conspicuity and recognition of cars, motorcycles, and bicycles as a function of intensity of the DRLs on cars. The intensity of the car DRL varied in five logarithmic steps from 0 cd to 25,000 cd. Cobb found that the identification of cars increased from no DRL up to a DRL intensity of 165 cd and then remained at the same level even for more intense DRLs. The identification of motorcycles and bicycles also increased up to a DRL intensity of 165 cd and then remained at that level up to a DRL intensity of 1,250 cd. Identification then dropped substantially when the intensity of the car DRLs was increased to 25,000 cd. Cobb's conclusion is that DRLs are primarily needed in cloudy daytime conditions. In those conditions, DRLs improve vehicle identification and do not mask bicycles or motorcycles.

Riemersma et al. (1987) studied the conspicuity of bicycles when close to cars equipped with DRLs. He found that while DRLs increased the conspicuity of the car, the conspicuity of the bicycle was not reduced. The above mentioned study of Cobb (1992) reached similar results. However, in the Danish evaluation of the effects of DRLs (Hansen, 1993), there were indications of increased collisions between cars and pedestrians. In the official German position paper (GRE, 2003a), this negative result is one of the main arguments against DRLs.

Attwood (1977, 1979) showed that it is more difficult to detect an oncoming car without DRLs between two cars equipped with DRLs than it is to detect the same car between two cars without DRLs or than it would be to detect the same car with DRLs between two other cars with DRLs. The effect was increased with lower levels of ambient illumination and stronger intensity DRLs. This finding was one of Attwood's (1981) main arguments for recommending that DRLs should not be more intense than 2,000 cd.

No studies of the masking of pedestrians as a function of DRL intensity have been found. However, several of the crash statistics studies show that unprotected road users benefit more from DRLs than do drivers and occupants in cars. Because DRLs do not make pedestrians and bicyclists more visible to drivers, it is likely that the unprotected road users more easily see vehicles with DRLs and can avoid collisions.

6.7. Masking of signal lights

DRLs may mask the signals from the front turn signals. Furthermore, if the rear lights are on together with DRLs, DRLs may also mask rear turn signals and brake lights. Baker et al. (1988) studied DRL masking of front turn signals. They could only find masking effects at longer viewing distances and with large DRL areas and when DRLs were the same color as the turn signal. The effect of intensity was limited. According to SAE (1990), DRLs with intensities of 5,000 cd or higher may mask front turn signals at close observation distances. At longer distances and at very short separations between front turn signals and DRLs, masking may already occur at a DRL intensity of 1,000 cd.

Färber et al. (1976) studied the masking of brake lights at 2º, 5º, and 10º peripheral observation angles. The ambient illumination level was 3,000 to 3,600 lux. Three separations between the position light and the brake light were used (same, close together, and 190 mm apart). Three taillight intensities (0 cd, 0.6 cd, and 6.0 cd) and three brake light intensities (4 cd, 20 cd, and 40 cd) were used. The observation distance was 30 m and the reaction time to detection was used as a criterion. No masking effects were obtained. Attwood (1981) could not find any evidence that rear position lights mask rear signals.

6.8. Glare

Kirkpatrick et al. (1987) studied discomfort glare from DRLs via rearview mirrors at a low level of ambient illumination (about 700 lux). The subjects considered DRLs of 1,000 cd just permissible. Kirkpatrick and Marshall (1989) studied discomfort glare at an ambient illumination level of 1,900 lux. Their results indicate that luminance, rather than intensity, determined the perceived discomfort glare. They also report that an intensity of 2,000 cd was just permissible to 80% of the subjects. The above-mentioned SAE studies (Section 6.1) showed that at very high ambient illumination (90,000 lux), even an intensity of 5,000 cd could be acceptable from glare point of view. Glare through rearview mirrors was studied by Kirkpatrick and Marshall (1989). They suggest that in order to limit that glare, the DRL intensity at 5º and higher should not exceed 1,000 cd.

6.9. Non-optimal DRL alternatives

CIE (1993) describes lamps and combination of lamps that could be acceptable as DRLs, although, for various reasons, not optimal from a lighting characteristics point of view. Standard low beams has proven its effectiveness in several studies and will probably continue to be accepted as DRLs for the foreseeable future. The problem with low beams as DRLs is not primarily their conspicuity performance but their costs (increased consumption of lamps and fuel) and environmental effect.

Other lamps acceptable as DRLs are reduced-intensity (e.g., by 30%) low beams (as frequently used in Sweden), standard fog lamps, reduced-intensity fog lamps, and cornering lamps. Reduced-intensity high beams (used in Canada and USA) are not overly desirable. Either the reduction must be so large that the peripheral intensity is very low, or they will create glare at already moderate levels of ambient illumination.

It is also possible to use some signal lamps as DRLs, such as turn signals or increased-intensity position lights (parking lamps). Based on an analysis of accident statistics of daytime collisions of paired GM and Saab cars the year before and after they were equipped with DRLs, Thompson (2003) compared the effectiveness of different types of DRLs. Over 900,000 vehicle records were collected from 17 states. He found that larger accident reductions were obtained by turn signal DRLs and dedicated DRLs, while smaller reductions were obtained with full-intensity low beams and reduced-intensity low beams.

In Canada it is acceptable to use full- or reduced-intensity low beams, reduced-intensity high beams, turn signals, increased-intensity parking lights, fog lamps, and dedicated DRLs (White, 1998).

The specific problems in designing DRLs for heavy-duty trucks are discussed by Carver and Josey (1988).

6.10. Effects on motorcycle conspicuity

Motorcycles have the highest crash rate of all motorized road users. One of the primary reasons for this is their poor conspicuity due to their small front surface area. A second reason is the difficulty in estimating the distance to and the speed of a motorcycle (again because of the small surface area). Even when low beams are on, it is much harder to estimate speed and distance for motorcycles than for cars, which have a larger front area and two headlights. A third reason is a possible confusion of identity between the fast motorcycle and the slow moped (their front views are almost identical).

Cercarelli et al. (1991) compared the crash patterns of motorcycles and cars and did not find any marked differences in daytime collisions. However, Donne (1990) estimated that about one-third of motorcycle collisions involve a perceptual problem from the other road user's point of view. Henderson et al. (1983) showed that motorcycle crashes were reduced by about 5% after the introduction of the DRL legislation for motorcycles in North Carolina in 1973. Other crashes were not influenced. Because of these findings, many jurisdictions (e.g., Canada, several U.S. states, Australia, Denmark, Germany, France, and Spain) introduced legislation concerning compulsory DRLs on motorcycles relatively quickly.

Motorcyclists generally favor DRL legislation because they think it is good for their safety. However, they are generally negative about DRL legislation for other motor vehicles, as they would like to be the only vehicles with DRLs. They fear that if everybody had DRLs the conspicuity of the motorcyclists would be reduced. There is some evidence that this may in fact occur, but only in specific situations (rural intersections) and the effect is not very strong (Brendicke et al., 1994). The official German position (GRE, 2003a) on DRLs is generally negative, and one of their main arguments is the fear for the increased risk for motorcycles if all vehicles were equipped with DRLs. Our interpretation is that if general DRL legislation is introduced (instead of DRL legislation only for motorcycles), motorcycles will remain equally conspicuous with other vehicles gaining increased conspicuity.

The problem with identification of motorcycles (e.g., distinguishing them from mopeds), could be solved by giving motorcycles a special DRL configuration (e.g., three lamps mounted in a triangle) (Fulton et al., 1988; CIE, 1993). More than one lamp would also facilitate estimation of distance and speed of motorcycles.

Also bear in mind that in most countries there are many more cars on the road than motorcycles. And, for many reasons, cars are far more dangerous to pedestrians than are motorcycles. Consequently, generally increased motor vehicle conspicuity will save many more lives than only increased motorcycle conspicuity.

6.11. Optimal lighting characteristics (area, intensity, luminance, light distribution, color, position)

There are no comprehensive studies of optimal characteristics of DRLs. There are, however, a number of studies that touch upon these questions. Most of them have been mentioned earlier in connection with the specific problems they have dealt with.

Both the ECE-R87 and the SAE Recommended Practice require a minimum surface of 40 cm^2 for DRLs (see Table 1). Hörberg and Rumar (1975) compared the peripheral conspicuity of 70 cm^2 and 200 cm^2 DRLs of different luminous intensities. Kirkpatrick et al. (1987) used the same range of DRL area but at higher ambient illumination levels. The results from both studies show no significant differences in detection distance.

Efforts are underway to amend ECE-R87 to reduce the minimum surface to 25 cm^2 (GTB, 2003). There are no studies of the effect of such small DRLs, nor is there any indication that there could be any conspicuity disadvantages worth mentioning with DRLs of that size.

ECE-R87 (which is intended for dedicated DRLs) specifies the minimum luminous intensity in the central part of the light distribution of 400 cd and the maximum in any direction of 800 cd. The amendment efforts mentioned above (GTB, 2003) suggest an unchanged minimum (400 cd) but an increased maximum (1,500 cd). However, in Europe there is concern that the luminance of a lamp with the minimum area (25 cm^2) and the maximum intensity (1,500 cd) would be too high and create discomfort glare. Therefore, a formula is specified which limits the luminance. This formula states that the intensity emitted in the direction of the reference axis shall not exceed 25 times the resultant value of the area of the apparent surface in cm^2 (measured in the direction of the reference axis). There is also a concern that the luminance of a lamp with the maximum area (200 cm^2) and the minimum intensity (400 cd) might be too low. Therefore, a corresponding formula states that the intensity (in cd) emitted in the direction of the reference axis shall be at least five times the resultant value of the area of the apparent surface (in cm^2).

SAE Recommended Practice J2087 (SAE, 1997), which is intended for all types of DRLs, not only dedicated DRLs, specifies no maximum area. The minimum intensity in the central part of the light distribution (for "Photometric Design Guidelines") is 500 cd and the maximum intensity in any direction is 7,000 cd.

Paine and Fisher (1996) have developed a formula for the calculation of signal range. Using that formula, Paine (2003) calculated expected signal range for a number of alternative DRL intensities on a bright but cloudy day (background luminance of 1,000 cd/m^2). His results show that in 3º peripheral vision, 400 cd DRLs would effectively reach about 320 m and low beams slightly farther. A DRL intensity of 800 cd would reach about 380 m, and an intensity of 1,200 cd about 550 m. His conclusion is that most of the evaluated DRLs would pass as acceptable DRLs from a signal range point of view. However, on a very bright and sunny day (background luminance of about 10,000 cd/m^2) only the most intense of the DRL alternatives would be acceptable as DRLs.

ECE-R87 requires that the color of the DRL must be white, while SAE accepts any color between selective yellow, yellow, and white. According to Sayer et al. (1999, 2001) the size of the Helmholz-Kohlrausch effect between white and yellow for luminous objects of small subtended angle, such as DRL, is 10 to 20%. Consequently, in our opinion, there is no need to have different intensity requirements for DRLs of different colors.

The SAE Recommended Practice for DRLs specifies that the two lamps on a car should be mounted symmetrically relative to the centerline of the vehicle, as far apart as possible, and at the same height (380 to 1820 mm). ECE-R48 (ECE, 2001) specifies that DRLs should be positioned not more than 400 mm from the extreme outer edge of the vehicle, not closer to each other than 600 mm, and at a height of 250 to 1,500 mm above the ground. In both SAE and ECE, a telltale is optional. However, SAE specifies that if it is installed it should be yellow and have a minimum projected illuminated area of 18 mm^2.

Sivak et al. (1999) found that narrowly positioned DRLs were more conspicuous than widely separated DRLs with the same intensity. It is however our opinion that narrowly positioned DRLs could impair distance estimations and therefore should be avoided. Sivak et al. (1997) studied glare from reduced-intensity high beam DRLs as a function of mounting height within a limited range (.84 to 1.37 m) and did not find any differences.

As indicated earlier (see Section 6.2.), future DRLs may adapt themselves to the actual ambient illumination level.

6.12. Light sources

Schug and Schiska (2000) compared different ways of implementing DRLs. Their conclusion is that an extra light source in the low beam reflector would impair the low beam too much. A dimmed high beam will be too narrow, and a stronger light source in the position lamp would not solve the problem. Therefore, they proposed separate (dedicated) DRLs or an extra light source in the high beam reflector.

Work is underway at light source manufacturers to develop light sources that will have characteristics suitable for use in DRLs. One such light source presently under consideration is P13W (de Visser, 2003). The new light sources primarily have much lower power consumption than the present low beam light sources. And considering that DRLs are supposed to be turned on for very long periods, long life lamps with low energy consumption (which do not generate much heat) should be used. Such requirements immediately lead to LED light sources. Recent advances in LED technology have opened new possibilities here. With combinations of LEDs, 400 cd is no problem (Albou, 2003). Currently, a single LED can produce about 180 lumens and within a couple of years an emitter is expected to produce close to 300 lumens (Hodapp, 2002).

6.13. Wiring and integration

In all discussions on how DRLs should be electrically connected there is unanimous agreement that DRLs should turn on and off automatically to avoid human errors. When low beams are turned on, DRLs should be automatically turned off and vice versa. Switching to and from low beams automatically as a function of ambient illumination would be an advantage.

A critical question is if other lamps should be turned on at the same time as DRLs. A decision on that point will, of course, influence the wiring of DRLs. This question will be discussed in more detail below (Section 9.3.3). However, it seems logical from a usage and simplicity point of view to propose that if standard low beams are used as DRLs, no change should be made in the wiring. All marker lights should be on as usual. But if some kind of dedicated DRL is used, it seems equally logical from cost, fuel, and environmental points of view to assume that no other light should be on at the same time as DRLs.

The SAE Recommended Practice for DRLs describes guidelines of how a telltale sign indicating DRLs should be designed. A telltale is not required if standard low beams are used as DRLs or if a sensor determines when DRLs vs. standard lighting is used. ECE-R87 does not deal with telltales. But ECE-R48 states that a telltale is optional for DRLs.

Swedish experience from early years of DRL usage showed that special DRLs, which were added to the front of the vehicle, were exposed to dirt, damage, and wear. DRLs should be integrated into the front of the vehicle so that they receive the same service and cleaning as other lamps.

7. GENERAL EFFECTS OF DRLs

The main reasons for having DRLs is to increase road safety by increasing motor vehicle conspicuity. Therefore the main positive effect to consider is the effect of DRLs on daytime collisions. The effects that are often considered negative for DRLs are costs in terms of increased fuel consumption and wearing out of lamps and environmental effects (pollution) due to the increased fuel consumption. The weighting between the positive and negative effects is often achieved by cost-benefit studies. In this section these general effects are described and analyzed.

7.1. Crash effects

There seems to be no doubt that DRLs reduce daytime collisions. Abundant amounts of studies are almost unanimous in this result. Unfortunately, many of the statistical studies suffer from methodological deficiencies. Elvik (1996) carried out a meta-analysis of 17 earlier studies of DRL crash effects. He came to the conclusion that the positive effect of DRL is very robust. Koornstra et al. (1997) have carried out probably the most careful and best analysis of the statistical investigations of the effects of DRLs on road crashes.

Koornstra et al. covered 24 available studies, including both national studies and fleet studies. They take into account the initial usage of DRLs at the time of the start of the study and the usage level at the end of the study, as well as the latitude of the study site. They distinguish between studies using accidents and studies using injuries as dependent variables. The results show that there are significant differences between fleet studies and national studies as well as between accident studies and injury studies. Most of the accident statistics studies reference low beams being used as DRLs.

Figure 1 on page 13 shows the main result of their analysis taken together. It shows the intrinsic effects of DRLs (the safety effect of a change from 0% use of DRLs to 100% use of DRLs) as a function of latitude. Elvik (1996) and Stone (1999) have, however, criticized their statistical assumptions in estimating the intrinsic effect of DRLs. They consider the increase of the DRL safety effect, which Koornstra et al. estimated based on the usage level at the time of the evaluation, to be too large. As shown in the figure, the safety effects on multiple daytime collisions are amazingly large. The largest effects are expected for fatalities, the next largest for injuries, and the smallest for accidents. According to Koornstra et al., DRLs should reduce injuries in daytime collisions by about 40% at a latitude of 60º (Helsinki, Oslo, Stockholm, Anchorage, Northern part of Antarctic), about 20% at a latitude of 50º (Paris, London, Winnipeg, Vancouver, Ulanbator, Falkland Islands), and around 10% at a latitude of 40º (Rome, Madrid, New York, San Francisco, Beijing, Sapporo, Melbourne, Wellington).

Farmer and Williams (2002) studied cars equipped with automatic DRLs in nine U.S. states and found that DRLs reduced multiple vehicle daytime crashes by 3.2%. That is lower than what the curve in Figure 2 would predict, but the studied states were mainly confined to the southern U.S.), unprotected road users were not included, and some vehicles were certainly also using lights even in the control states. These differences could explain the lower figure. Germany, in its negative official position (GRE, 2003a), is very critical of the study by Koornstra et al., and argues that they overestimate the positive effects of DRLs and underestimate the negative effects.

GM carried out two of the most recent fleet studies (Bergkvist, 2001; Thompson, 2003). GM started equipping their cars sold in the U.S. with DRLs in 1995. Since 1997, all GM cars sold in the USA are equipped with DRLs. The most recent analysis (Thompson, 2003) estimates that GM drivers, through 2001, have avoided more than 37,000 vehicle collisions thanks to DRLs. On the basis of its experience, GM has petitioned NHTSA (GM, 2001) to require DRLs in the USA (see Section 8).

A recent French study of a DRL campaign (Lassare, 2002) claims that those using DRLs had a 60% reduction of fatal daytime collisions on large roads (!). So far it has not been possible to obtain further information on this study.

The results of the various studies seem to indicate that the largest crash reduction effects due to DRLs appear for crashes between cars and unprotected road users (larger than what is shown in Figure 1). That is in line with the Swedish and U.S. studies (Andersson and Nilsson, 1981; NHTSA, 2000; Bergkvist, 2001). In his study of the effectiveness of various types of DRLs, Thompson (2003) found that the largest accident reduction as an effect of DRLs involved vehicle-to-pedestrian collisions (about 10%). The largest reduction within this category was obtained for pedestrians under the age of 12.

Swedish experiences indicate that pedestrians intending to cross the street and bicyclists intending to make a turn detect approaching vehicles much more easily if they are equipped with DRLs. Older persons frequently report that they are very satisfied with DRLs. A possible reason for this opinion is that older persons often have reductions in functional visual field, contrast sensitivity, and ability to turn their heads. The positive DRL effect on older persons has been confirmed by Perel (1991).

7.2. Fuel consumption and wearing out of light sources

The proportional increase in fuel consumption due to DRLs depends on the weight of the vehicle, type of DRLs (e.g., full low beams or LEDs), and whether other lights are on at the same time as DRLs. For a large truck with a general fuel consumption of about 3 liters per 10 km, the additional petrol consumption of low beam DRLs would be less than 1% while for a small passenger car with a general petrol consumption of 0.5 liters per 10 km, the additional consumption due to low beam DRLs might reach 3% (Koornstra et al., 1997).

Several studies measured the additional fuel consumption caused by DRLs (NTR, 1976; Kaehn, 1981; Lawson, 1986; BASt, 1989; Schoon, 1991). The two most recent studies estimate a 1.6% increase for a typical passenger car when using standard low beams as DRLs. If we assume that about 70% of the annual mileage is carried out in daytime, we can estimate that if all vehicles used full low beams as DRLs (including rear lights), the increased annual fuel consumption would be 1.1%. For lower energy-consuming light sources, like 13 W bulbs or LEDs, and without other marker lights, the increase would be less than 0.5%.

The burning out of light sources (low beams and other lights) can be estimated to increase by a factor of 2.5. The extra costs for replacing burned out light sources could be on the order of $ 6-10 annually (Schoon, 1991). With LEDs as DRLs, and no other lights, the extra costs for lamps would be almost negligible.

7.3. Environmental effects

The increased exhaust pollution due to DRLs is directly proportional to the increased fuel consumption due to DRLs, and is consequently on the order of about 1%. The environmental costs of automobiles will consequently increase by about 1%. Again, with LED-based DRLs and no other light sources, the environmental costs of DRLs are reduced to less than half of a percent.

It is our firm belief that environmental arguments will increase in weight in the coming years. Environmental impact, fuel consumption, and costs will be stronger considerations in the future development of automobiles. Therefore, we give them a high value concerning the functional requirements of DRLs.

7.4. Benefit and cost studies

Koornstra et al. (1997) have carried out what is probably the best analysis of the cost benefit of DRLs. While we do not quite agree with all their assumptions (e.g. intrinsic effects, daytime mileage), we share their approach. The drawback is that the total effects are directly applicable only to the European Union.

The costs of automatic, compulsory DRLs may be divided into four parts:

- Fuel costs
- Environmental costs
- Light sources (replacement)
- Vehicle costs (wiring, lamps, switches)

The first three costs have already been discussed. The vehicle costs will be high initially, but successively get lower, and after a few years probably become close to negligible.

The benefits depend primarily on latitude and the costs set for a fatality, a serious injury, a slight injury, and an accident. A few years ago, the European Union agreed to set a price of one million ECU (USD) on the costs resulting from a road fatality (including the cost of injuries and the material costs normally related to a fatality).

Koornstra et al. (1997) apply these figures to the 15 countries in the European Union and come to the conclusion that the benefit/cost ratio is just below 2. That is to say, for every $1 invested, the return is $2. It would be higher in the Scandinavian countries and lower in southern Europe. Paine (2002) comes to similar conclusions for dedicated DRLs. However, Paine concluded that retrofitting automatic low beams as DRLs would not be cost effective. In contrast, Toffelmire and Whitehead (1997) are not convinced about the cost effectiveness of DRLs.

8. STUDIES IN PROGRESS

The European Commission recently started an evaluation of the effectiveness and costs of existing DRL legislation with the goal of proposing an implementation strategy for DRLs to the European Union. The research is performed jointly by TNO in the Netherlands, TØI in Norway, SWOV in the Netherlands, VTT in Finland, and the Free University of Amsterdam in the Netherlands. A final report is expected in 2004.

Paine (2003) is carrying out a review of DRLs for the National Roads and Motorists Association in Australia. He reviews what has been done with DRLs, adds some new data, and comes to the preliminary conclusion that DRLs are no doubt good from a road safety point of view, but that the low beam DRL solution is not cost effective enough to motivate a compulsory requirement of automatic low beams on all vehicles. The review is not yet released.

Within GTB, work is underway to propose amendments to the ECE-R87 regulation on DRLs (GTB, 2003). At a GTB meeting in the fall of 2002, a DRL Task Force was appointed to suggest amendments to ECE-R87 based on two proposals from Belgium and Germany. The present proposal (see Section 5.7.) is to allow a smaller DRL area (25 cm^2) and a higher luminous intensity (1,500 cd). In order to also regulate the luminance, formulas limiting the maximum and minimum luminances are also outlined (see Section 6.11). This proposal will be discussed during 2003, and a proposal to GRE/WP29 is expected by the end of the year.

SAE also has a Task Force on DRLs whose goal is to develop a common set of functional requirements for all types of DRLs, including low beams, turn signals, and dedicated DRLs (Woodward, 2002).

As indicated earlier, GM has petitioned NHTSA to require DRLs in the USA (GM, 2001). NHTSA has not yet responded to this petition. However, in 1998 NHTSA announced a Notice of Proposed Rulemaking concerning DRLs in the Federal Register (NHTSA, 1998). NHTSA stated that they would like to limit the glare from DRLs in three steps: first to 3,000 cd for reduced-intensity high beams, then to the same value for low beams, and finally four years after implementation to 1,500 cd for all DRL alternatives. None of the three stages has been implemented thus far.

Transport Canada has received many complaints about drivers using DRL options without rear lights in situations with lower ambient illumination levels, and it is considering requiring signal lights to be turned on with DRLs (White, 1998).

The European Automobile Manufacturers Association (ACEA) offered the EU a voluntary agreement in 2001, including, among other things, introduction of DRLs on all new cars but only if the proposed, more stringent requirements for the design of the fronts of cars for improved pedestrian protection could be avoided. The European Union has not yet made a final decision concerning this proposal.

9. CONSIDERATIONS

In this section, positive and negative effects of DRLs are considered and discussed. Furthermore, some major unanswered questions are discussed in order to arrive at recommendations.

9.1. Positive effects

Initially, DRLs were used as a symbol of safe driving. But fairly soon it was realized that DRLs may in themselves be an effective safety measure. Daytime collisions constitute about half of all crashes and they are caused primarily by late detection. Perceptual studies show convincingly that vehicle conspicuity, primarily in the periphery but also in the central visual field, is considerably enhanced for DRL-equipped vehicles. Furthermore, behavioral studies show that DRLs make estimating the distance and position of oncoming vehicles safer. Also, DRLs could facilitate both vehicle identification and recognition that the vehicle is active (engine running).

The national and fleet crash studies carried out differ considerably in quality and methodological control. However, after careful analysis and corrections they still they offer convincing evidence of DRLs' ability to reduce daytime collisions (Koornstra et al., 1997). Figure 1 illustrates the total reduction of daytime collisions that could be achieved by introducing DRLs. Most of the accident statistics studies refer to low beams being used as DRLs. However, Thompson (2003) has compared the effectiveness of various types of DRLs using accident statistics. He found that the largest crash reduction affects were obtained with turn signals used as DRLs. Dedicated DRLs were not quite as good as turn signal DRLs but were more effective than full-intensity low beams and reduced-intensity low beams. (Thompson's report does not describe in detail the lighting characteristics of the various types of DRLs involved in the study.)

Unprotected road users, who have a higher risk in road traffic than drivers or vehicle occupants, appear to benefit most from DRLs (Andersson and Nilsson, 1981; NHTSA, 2000; Bergkvist, 2001; Thompson, 2003). DRLs make it easier for them to see approaching cars, and thus they can avoid collisions that might otherwise occur.

9.2. Negative effects

Section 3.3 mentioned a number of potential risks involved in the introduction of DRLs. Many of these potential risks could be dismissed based on empirical evidence (novelty effect, masking of signal lights, impaired conspicuity of motorcycles, and compensatory driver reactions). The glare problems are a hot issue, especially in the U.S., where NHTSA has received numerous complaints (NHTSA, 2001). However, glare is a much more difficult question concerning low beams than DRLs. Public reactions, like the present ones in the USA, must however be taken into consideration. DRLs must not have characteristics that will be perceived as glare; otherwise DRLs will be very difficult to market to the public.

Motorcycles should be further enhanced, and their speed and distance should be made easier to estimate, perhaps by creating a triangular pattern of a DRL lamp and two other lamps of DRL type and characteristics.

Other potential risks have been confirmed (impaired conspicuity for cars not having DRLs, masking of other road users, and glare at low levels of ambient illumination). DRLs must be designed in such a way that these negative effects are either eliminated or considerably reduced.

Other negative effects of DRLs are indisputable. DRLs lead to increased fuel consumption and the resulting increased pollution. These effects are limited (to about a 1% increase) and could be further reduced by a suitable design and wiring of the DRL (possibly to a less than 1/2% increase). These effects will increase in importance in the coming years. In many of the DRL alternatives discussed (see Sections 6.9 and 9.3.1), the costs of worn out light sources and an increased number of "one-eyed" vehicles may also be considerable.

These negative effects will be considered when we discuss an optimum design for DRLs.

9.3. Unresolved questions

There are three main unresolved questions concerning DRLs:

1. Which type of existing automobile front lamps should be accepted as DRLs?
2. What would be an optimal light distribution for a dedicated DRL?
3. Should the various other lamps (e.g., rear lights, side lights, front position lights, license plate lights, and instrument lights) be used at the same time as DRLs?

9.3.1. Lamp types acceptable as DRL

Most accident statistical studies were carried out with standard low beams as the dominating DRLs. Therefore it is logical to accept low beams as DRLs for at least a considerable transition time. Low beams, however, have several disadvantages, which make them less than ideal as DRLs. Most of the light (and energy) is aimed in the wrong direction (downward), the costs in fuel and lamp consumption are considerable, and the impact on environment is unnecessarily large (especially if all marker lights are on with the DRLs). Therefore, in the long run, low beams should not be used as DRLs.

Another acceptable temporary DRL lamp alternative is reduced-intensity low beams (see Section 6.9). Standard fog lamps and reduced-intensity fog lamps are more questionable because they are often auxiliary lamps, poorly aimed, and poorly maintained. Also, they are often positioned very low.

Then there are a number of DRL alternatives that are based on modifications or combinations of lamps (e.g., turn signals, cornering lights, reduced-intensity high beams, and increased-intensity position lights). DRL alternatives are acceptable, provided they meet the requirements proposed for dedicated DRLs (see Section 9.3.2). (Thompson (2003) presents crash data indicating that turn signal DRLs and dedicated DRLs are more effective than some other implementations.)

9.3.2. Requirements for dedicated DRLs

The improved conspicuity effect of DRLs is stronger the lower the level of ambient illumination (Collard, 1995). However, if the ambient illumination is low enough, drivers will need headlight illumination to drive safely, and they will be sensitive to glare from opposing intense light sources. Therefore, there seem to be two alternatives in which ambient illumination dedicated DRLs should work.

Dedicated DRLs could be designed for lower levels of daylight and for twilight (dawn and dusk), but then other lamps (primarily rear and front position lamps, and side lights) must also be on at the same time as the DRLs so as not to impair vehicle visibility from the rear and sides. If this condition is chosen, the acceptable dedicated DRL intensity must be comparatively low in order to avoid glare and masking of other road users.

Another option would be to design the dedicated DRLs for moderate levels of daylight, and use standard vehicle lighting (low and high beams) at lower levels of ambient illumination. Then no other marker lights need to be on along with the dedicated DRLs and the acceptable intensity level of the DRLs can be made stronger.

The question of where the limit of ambient illumination between these two situations is situated is not quite clear from the available literature. The SAE Recommended Practice uses 1,000 lux vertical illumination as a suitable limit. In our opinion, that level is acceptable although somewhat low. Lindeijer and Bijleveld (1990) studied the percentage of drivers using low beams as a function of ambient illumination. They found that in dry and clear weather, about 70% of the drivers used low beams at 1,000 lux ambient illumination and at 1,500 lux, only 20% of the drivers used low beams. In wet weather, the usage of low beams was higher. We would therefore propose to use 1,500 lux ambient illumination as the limit between using low beams and dedicated DRLs.

Consequently, before we start a discussion of suitable lighting characteristics of dedicated DRLs, we have to make a decision concerning the ambient illumination levels that DRLs should be designed for. Our conclusion of this analysis is that DRLs should primarily be designed for moderate levels of daytime illumination, or approximately 1,500 lux to 40,000 lux. The main arguments for this position is that at lower levels of ambient illumination (< 1,500 lux), the glare and masking effects are too high; at higher levels of ambient illumination (> 40,000 lux), DRLs must be so intense to increase vehicle conspicuity that they will also create glare at moderate levels of ambient illumination. Furthermore, at lower levels of ambient illumination, the driver should use standard headlamps (primarily low beams) to see better. Finally the need for enhanced conspicuity is limited at very high levels of ambient illumination.

Increased DRL intensity means both increased conspicuity and increased risk for glare. The problem is finding a DRL intensity range for the relevant ambient illumination range in such a way that the conspicuity benefit is obvious while the glare disadvantage is low.

Hagenzieker's (1990) conceptual summary of the results of the available studies of DRL characteristics and their conspicuity is helpful in answering this question. To summarize all the results is not an easy task, considering that there are various differences among all the studies. However, the summary is illustrated in Figure 3, where DRL effectiveness is shown as a function of ambient illumination and DRL luminous intensity. We have modified the figure by taking away parts that are irrelevant to our task. The lower line in the figure indicates when DRLs improves conspicuity and the upper line indicated when they start to create glare. Our interpretation of the various results is based on this figure; Hagenzieker did not use it to derive any intensity recommendations.

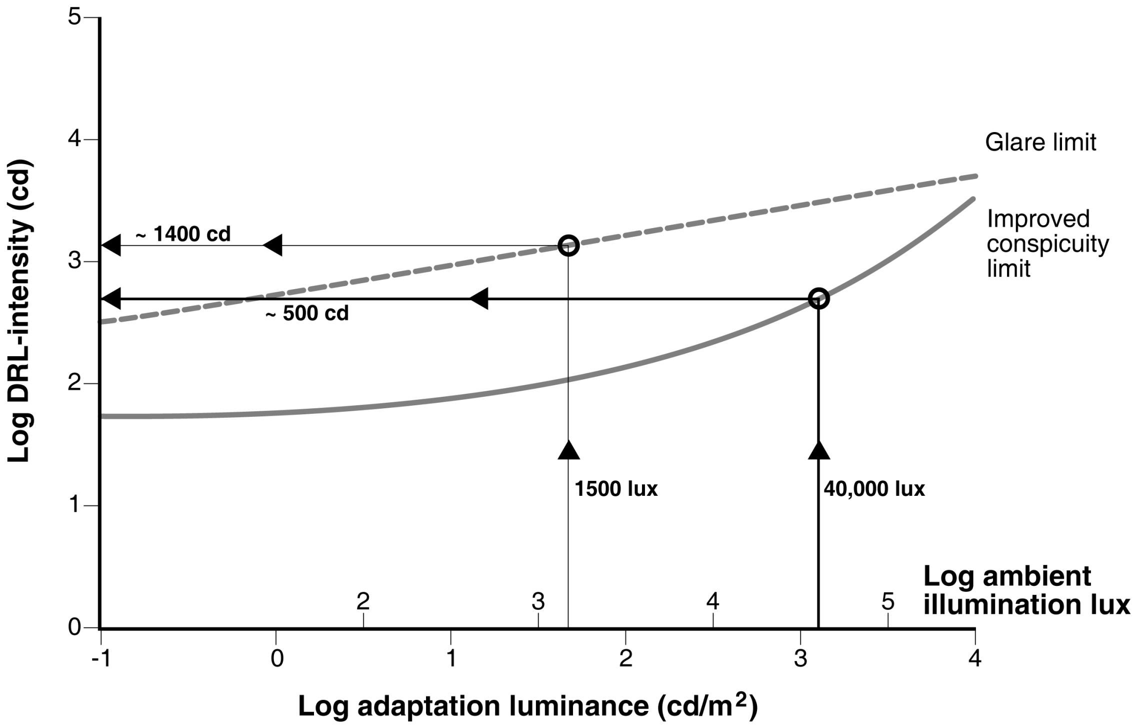

Figure 3. A summary of the various DRL studies concerning DRL intensity (after Hagenzieker, 1990). The solid, lower curve indicates the level at which DRLs will improve conspicuity; the dashed, upper curve indicates the level at which DRLs will create undesirable levels of glare. The vertical lines indicate the proposed range of DRL functionality (1,500 lux to 40,000 lux) and the corresponding horizontal lines indicate the maximum and minimum DRL intensities.

Hagenzieker used background (adaptation) luminance to indicate the level of ambient illumination. Using data from Kirkpatrick and Marshall (1989), we have indicated the corresponding ambient illumination in lux in the figure. Taking this figure as a basis for our decision, we start with our lower level of ambient illumination at which DRLs should be functional (1,500 lux). We then check at which intensity undesirable levels of glare would start to occur, which is the maximum potential intensity for a DRL. This turns out to be about 1,400 cd. We then go to our proposed maximum ambient illumination, within which DRLs are supposed to improve vehicle conspicuity as argued above (40,000 lux), and check at which intensity level DRLs will start to improve vehicle conspicuity. That is the potential minimum intensity level for a DRL and it turns out to be about 500 cd.

Let us now look at two existing DRL requirements. The present minimum luminous intensity is 400 cd in ECE-R87 and this is also recommended by CIE (1993). In U.S. FMVSS 108 the minimum is slightly higher, 500 cd. Both these values are acceptable. However, the maximum luminous intensity in the present ECE-R87 (800 cd) seems to be too low for conspicuity reasons and the present maximum luminous intensities in FMVSS 108 (3,000 cd anywhere in the beam, or 7,000 cd in the center of the beam if high beams are used) are too high for glare reasons. Furthermore, a very high-intensity DRL would not encourage drivers to switch on headlamps at low ambient light levels.

GTB (2003) is considering increasing the present maximum from 800 cd to 1,500 cd. NHTSA (1998) is considering decreasing the maximum intensity in the U.S. in several steps from 7,000 cd to 3,000 cd to 1,500 cd. Consequently, the two requirements, which were originally very different, seem to be converging on a maximum intensity of 1,500 cd.

Based on the reasoning above and the fact that a value somewhat lower than 500 cd would be effective in enhancing vehicle conspicuity within the major part of the intended range of ambient illumination, we propose a minimum luminous intensity of 400 cd for a dedicated DRL. Furthermore, we argue that a slight discomfort glare at lower levels of ambient illumination presents no danger if it would enhance vehicle conspicuity in the upper values of the intended illumination range. We therefore propose a maximum intensity of 1,500 cd.

With an intelligent DRL that adapts itself to the ambient illumination level, it will not be necessary to make this decision, which in all cases is at best a compromise.

Especially in Europe, discomfort glare is a sensitive matter. That is one of the reasons why in the proposed amendment to ECE-R87, GTB (2003) is proposing formulas to regulate the minimum and maximum luminances of DRLs (see Section 6.11). From a conspicuity point of view, the luminance of the DRLs probably has no substantial effect. The sensitivity in the periphery of the eye is good for intensity differences but low for luminance differences. Therefore, the main argument for introducing a luminance limitation in the DRL lighting characteristics offers very limited advantages in terms of discomfort glare. We feel this decision is questionable and will only unnecessarily complicate requirements. As long as we have not done anything along the same lines for headlights, with much higher luminance, why should we do it for DRLs? Consequently, the acceptable size of a dedicated DRL should be between 25 cm^2 and 200 cm^2.

However, DRLs smaller than 25 cm^2 would have a very high luminance and would easily be obstructed. And DRLs larger than 200 cm^2 would have a very low luminance and would occupy too much of the car front (see Section 6.11).

From a perceptual point of view, the color of DRLs could be anywhere between white (ECE-R87) and selective yellow (SAE). A problem here is that ECE has decided that yellow should be used primarily for lighting on the side of a vehicle. SAE does not have this limitation and in the USA amber is used for front turn signals (which have proved to work fine as DRLs). The yellow color is a rather poor symbol for the side of a vehicle because it is difficult to recognize in many real-life situations. To use a pattern consisting of several lights or a form (like the round form of tires) would be much better. It seems to us that based on pure perceptual considerations and also in the interest of global harmonization, we should accept white or yellow or anything in between as a suitable color for DRLs. Furthermore, yellow is, if anything, more conspicuous than white, which can blend with the fairly gray and unsaturated road scene background. However, we see no compelling reason to propose different intensity requirements for the various colors.

DRLs should be close to the low beams to make it easy to identify the vehicle and facilitate distance estimation. They should not be too far away from the headlamps, toward the center of the grill. They should not be too low because of potential dirt accumulation and obstruction on hills, or too high because of distance estimation problems and low contrast against the sky.

Light distribution is of primary concern for the central part of DRLs. On the other hand, Kirkpatrick et al. (1987) recommend that the maximum intensity of DRLs should be directed about 10º to the left to be of maximum benefit to the oncoming driver on a two-lane road and to avoid glare in rearview mirrors. That angle seems too large and it is primarily when a vehicle is coming toward you that it is potentially dangerous. The only exception is at intersections, when 45º left and right angles are relevant. There is not much need for DRLs in the vertical direction. Consequently, there is no need for requirements above 5º upward (pedestrians and truck drivers) and below 5º downward (vertical curves). In the new GTB proposal (GTB, 2003), the requirements of the DRL light distribution are identical to the present R87, except that the requirements for angles below 5º down are deleted. It is simply proposed that outside the requirements for the DRL light distribution and inside the requirements for DRL geometric visibility (ECE-R87), the minimum intensity of the DRL shall not be less than 1 cd.

A suitable light distribution for a dedicated DRL is suggested in Figure 4. It might be hard to achieve the 5% light distribution at 45º both left and right (as shown in Figure 4). A possibility could be to require 5% light distribution at 45º left only for the left DRL and 5% at 45º right only for the right DRL. But all the other requirements should be met by both DRLs. The angle 45º is selected because it corresponds to the angular location in a driver's field of view that will be occupied by a vehicle in potential conflict if the driver is approaching a right-angle intersection and the other vehicle is approaching on the cross street at about the same speed. SAE J2087 (SAE, 1997) requires an unobstructed view of DRLs at 45º, although it does not have an explicit photometric minimum at that angle. The value suggested here (5% of the minimum at the optical axis) is based on the expectation that the distances at which this wide light will be relevant will normally be much shorter than the distances corresponding to the more central points. During encounters on straight roads, drivers often have to detect oncoming vehicles at long distances (e.g., hundreds of meters, especially if a driver is contemplating an overtaking maneuver), whereas at intersections the important distances will normally be an order of magnitude shorter. This is partly because of lower speeds at intersections and partly because potential views of vehicles at longer distances on cross streets will often be obstructed by buildings and other visual barriers, rendering the visibility of the vehicle itself irrelevant. Because of the inverse square law, the minimum effective intensities at shorter distances are much lower.

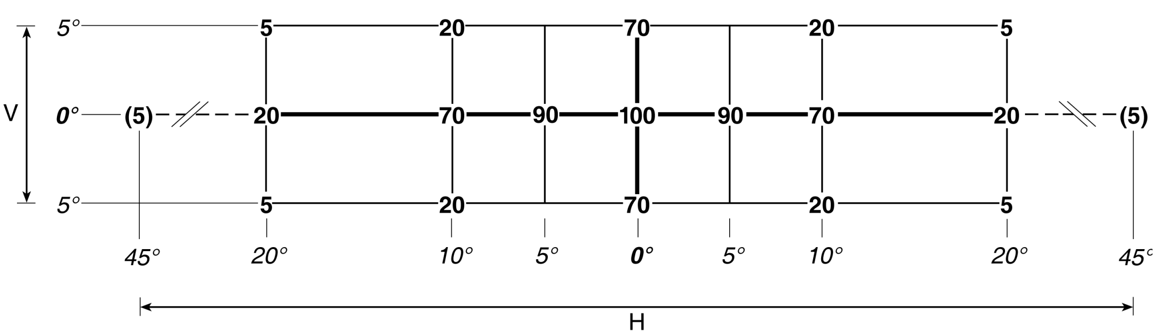

Figure 4. Proposed required light distribution (as percent of minimum at HV) for a dedicated DRL. The proposed minimum luminous intensity in the central part of the light distribution is 400 cd and the proposed maximum luminous intensity in any direction is 1,500 cd. The requirements at 45º (in parentheses) could be one sided (only required for the lamp on that side of the vehicle).

9.3.3. Other lights and DRLs

Should various other lamps be used at the same time as DRLs? The answer to this question lies partly in the decision made in Section 9.3.2 above, where it was stated that dedicated DRLs should be designed for moderate levels of daylight. Partly it is a question of how much weight is given to the environmental and cost aspects. These arguments lead to a proposal to use normally standard low beams at lower levels of daylight. And consequently, other light sources should then not be used together with dedicated DRLs. They will be automatically turned on when the low beams are turned on, which is when they are needed. Such a solution is also favorable from a cost/effectiveness and environmental point of view.

However, if standard low beams are used as DRLs, it is equally logical to argue that other marker lights should be on with the low beam. The illumination offered by other DRL alternatives is not a replacement for low beams, and consequently drivers (or an automatic system) should switch on the low beams (and other light sources) when the ambient illumination and weather conditions require. Therefore, other light sources should not be used together with those DRL alternatives. We must encourage drivers to use low beams as soon as the ambient illumination level is low enough.

These considerations encompass the entire scenario, and are illustrated in Table 1.

Table 1
Summary of the DRL proposals for four different DRL alternatives.

Characteristics	Dedicated DRL	Low Beams	Reduced low beams	Other DRL alternatives
Maximum intensity in any direction	1,500 cd	According to low beam regulations	Maximum 75% reduction in voltage	1,500 cd
Minimum intensity centrally	400 cd	According to low beam regulations	Maximum 75% reduction in voltage	400 cd
Size of apparent surface	25 – 200 cm^2	----	----	25 – 200 cm^2
Light distribution	See Figure 4	According to low beam regulations	Maximum 75% reduction in voltage	See Figure 4
Color	White to selective yellow	According to low beam regulations	According to low beam regulations	White to selective yellow
Other marker lights on with DRL	No	Yes	No	No
Automatic on at start	Yes	Yes	Yes	Yes
Automatic off when low beams on	Yes	----	Yes	Yes
Automatic off when engine off	Yes	Yes	Yes	Yes
Telltale	Compulsory	According to low beam regulations	Compulsory	Compulsory

10. RECOMMENDATIONS

Based on the present review we recommend the following:

- To reduce daytime collisions in urban and rural areas, compulsory and automatic DRLs should be legislated for all motor vehicles using public roads.
- The DRL requirements should include both new and old vehicles. However, older vehicles could receive a grace period before being required to install automatic switching.
- Before any DRL legislation is implemented, intensive information campaigns should be carried out to educate the public about the rationale and effects of DRLs.
- Motorcycles should be equipped with two horizontally-separated DRLs, placed under the existing DRL, to create a triangular DRL system.
- During the foreseeable future, standard low beams should be accepted as DRLs and a number of other standard lamps could be accepted as non-optimal DRL alternatives (see Section 9.3).
- The use of other lamps for DRLs could be nationally regulated.
- DRLs (except standard low beams) should only be used under moderate and higher daytime conditions (not below 1,500 lux of ambient illumination). At lower levels of ambient illumination and in seriously reduced visibility conditions due to inclement weather, standard headlights should be used.
- No other vehicle lights (front, side, rear, or instrument) should be on at the same time as a dedicated DRL, reduced low beams, or any modification or combination of other front automobile lamps meeting the dedicated DRL requirements.
- When standard low beams are used as DRLs, the other lights (front, side, rear, and interior) should be used together with the low beams.
- A compulsory, highly visible orange telltale should indicate that the DRLs and not headlights (with signal lights) are switched on. Alternatively, the standard headlights and marker lights should be switched on (and off) automatically at a certain illumination level.

- The recommended suitable light distribution of a dedicated DRL is shown in Figure 4.
- The maximum luminous intensity in any direction of a dedicated DRL should not exceed 1,500 cd.
- The minimum luminous intensity in the central part of a dedicated DRL should not be lower than 400 cd.
- With an intelligent DRL that adapts itself to the ambient illumination level, these limits would not be necessary. Such a development is recommended.
- The area of the dedicated DRL should not be smaller than 25 cm^2 and not be larger than 200 cm^2.
- The color of dedicated DRLs could be white, yellow, selective yellow, or any color in between. The intensity requirements for the various acceptable colors should be the same.
- A dedicated DRL should be positioned close to the headlamps, preferably even integrated with them.
- To reduce fuel consumption, exhaust pollution, and lamp cost and wear, the light source in a dedicated DRL should consist of one or more LED or a special low-wattage, long-life bulb.

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