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HISTORICAL DEVELOPMENT AND CURRENT EFFECTIVENESS OF REAR LIGHTING SYSTEMS

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16. Abstract

This report presents a historical account of the development of rear lighting systems. The account is based partly on a comprehensive review of the available documented sources. Various details of both technical developments and lighting standards are covered. Then the rear end crash situation is discussed. It is noted that rear end crashes constitute a large and increasing problem in present road traffic. This is followed by an analysis of the various functions of rear signaling systems and the extent to which the present rear lamps accomplish those functions. In the final section, the tasks of the driver in car-following situations are discussed, followed by a listing of possible changes to rear signaling systems that could enhance the safety of road transportation. (The report contains 191 references.)

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Executive Summary

Rear end crashes are one of the largest crash and injury problems in road traffic. In the U.S., they constitute close to 30% of all crashes, and account for about 25% of injuries in road traffic that lead to permanent impairment. Could improvements in rear lighting systems reduce this serious problem and facilitate the driver's task of interacting with other road users? We will be better able to answer this question by understanding how the present rear lighting systems have developed and how they currently function. In this report, we review the history and current status of rear lighting systems, limiting ourselves to the North American and European situations primarily because information from other parts of the world was not readily accessible.

Humans, as well as other species, have always used signals to facilitate interaction. When motorized vehicles were introduced, we started to move at higher speeds and also at night. It became important to communicate at longer distances, as well as in darkness. The first automobiles were equipped with the same lamps used on horse drawn carriages at the end of the 1890s. Candles and kerosene lamps were located in the front of the vehicle, and were primarily intended to make the vehicle visible to other road users. In the rear, there were no lamps. In the beginning of the 1900s, the front lamps became first acetylene and later electric. The first rear lighting (normally one kerosene lamp) was introduced just before the turn of the century to provide license plate illumination. It was common to equip the license plate lamp with a red opening towards the rear, thereby creating the first tail lamps. Not until about 1920 did most cars have electric lamps in both the front and rear.

During the 1920s, the first national and international regulations and standards on rear lighting appeared. Presently there exists a well developed national and international organizational structure for standards and regulations. On the international level, the most active organizations are UN/ECE, ISO, CIE, and GTB. In the U.S., SAE and NHTSA are the most prominent organizations. Corresponding organizations exist in other countries as well. Presently, the two largest comprehensive regulatory systems are published by ECE in Europe and NHTSA in the U.S. In both cases, the first regulations on rear lamps were established in the 1960s.

In 1926, the predecessor of the UN, the League of Nations, agreed on the first conventions related to automobile lighting. It was then agreed that during the night every motor vehicle must have a red lamp in the rear, and that the rear registration plate must be illuminated. Specific photometric requirements for tail lamps appeared first in the 1920s. They successively developed from a minimum of 0.1 cd and a maximum of 5 cd in 1928, to a minimum of 2.0 cd, and a maximum of 15 cd in 1955, along with a detailed specification of the light distribution. The 1955 requirements are essentially still valid in 1999. Two tail lamps became common in the 1930s in the U.S. and became a requirement in Europe in the 1950s.

The first brake lamps appeared as early as 1905. By 1928, requirements for brake lamps were introduced in eleven states in the U.S. More general requirements for brake lamps did not come until the 1960s. The photometrics of brake lamps have gone through a development similar to tail lamps: from the requirement that there should be one lamp, to a photometric requirement, to a light distribution, and eventually to a requirement for two lamps. The latest major development in brake lamps came in the 1980s—the center high mounted stop lamp (CHMSL).

The first turn signals appeared in the 1920s. In the 1930s, the first requirements were established both in Europe and in the U.S. However, the development was slightly different in that Europe favored the semaphore arm while the U.S. favored flashing turn signals. The flashing turn signals did not become common in Europe until the late 1960s. The photometric requirements for turn signals have gone through the same pattern of development as those for the other rear lamps.

Rear fog lamps were introduced in Europe in the 1960s. The first ECE regulation came in 1974 and rear fog lamps were made compulsory in Europe in 1991. However, in the U.S., they are still not mandatory. The first back-up lamp appeared as early as the 1920s. It was first standardized in the U.S. in 1947 but did not become mandatory until the late 1960s.

Following the historical review of rear lighting systems, the rear end crash situation is analyzed. It is concluded that the existence and design of rear lamps have a considerable influence on rear end crashes, especially at night. Then the tasks of the rear lighting system are analyzed and an evaluation is made of the extent to which the current systems meet the demands of these tasks. Seventeen specific tasks are listed. It is concluded that in respect to several of these tasks the present rear lamps do not meet optimum requirements.

In the final section, the task of the driver in car-following situations and the implications for rear lighting design are discussed. That is followed by a discussion of possible changes to rear lighting systems that have the potential to enhance the safety of road transportation.

Contents

1. Why Do We Have Signals and How Have They Developed?

1.1. Natural signals

When several animals move in a common environment, they have to interact in order to avoid conflicts. Their interactions may be based on numerous explicit and implicit signals: rank, size, speed, body language, visual contact, and sound. Most of the signals are inherited while some are developed by experience. When people walk in the same area, they interact very much by the same means. This was the situation for our ancestors, and this is the situation for us. The two main requirements of signals are that they should be easy to detect and easy to interpret.

In the early stages of human development, the signals that were employed were probably mainly inherited. They did not require any intellectual effort. A given signal was immediately and unconsciously followed by a certain behavior. This process is what Schneider and Shiffrin call automatic processing (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). Gradually, along with the development of artificial physical tools, people developed the abstract tools of artificial signals for communication. The first artificial signals that were developed by humans to communicate at long distances probably included light or smoke signals. In nighttime, fires were used to lead (or mislead) ships and to warn other villages about approaching enemies.

When people started moving by means of horse, carriage, or bicycle, the same basic interaction signals were used. Since the speeds and energy levels when using such modes were much higher than when moving by foot, interaction had to take place at longer distances in order to avoid conflicts. Therefore, hand signals and sound signals (e.g., bells) were introduced to make possible simple interaction at a distance. When people became involved with the first generations of motor vehicles, interactions were very much the same as when they were moving on horses and bicycles. The main difference was that the speeds and energy levels involved were even greater, so that signals needed to be perceived at even longer distances. This led to the introduction of special motor vehicle signals, (e.g., the horn). Detecting and understanding such signals was more abstract and less natural. Schneider and Shiffrin call this conscious process controlled processing. Signals that require controlled processing are often processed more slowly. However, after extensive learning periods, signals originally requiring controlled processing may be processed automatically. Automobile signal lamps are such an example. The existence of automatic reactions to vehicle signal lamps is also one of the stronger arguments against changing an established signaling system.

1.2. The early generations of motor vehicles

A human generation is now about twenty-five years. A passenger-car generation is probably not longer than ten years (trucks and buses have longer generations). Let us say the automobile was born about 1890. This means that by now we are in about the eleventh generation. Not every system in the car changes with each generation. Rear lighting is probably one of the systems that have changed the least over these generations.

One reason for the development of special motor-vehicle signals was the fact that people started moving not only during the day, as was originally the case, but also at night. In darkness the original signals, whether they were natural or artificial, were not visible. Thus, there was a need for self-luminous signals, which, if strong enough, could also be used during daylight hours. However, during daylight hand signals and other man-made signals were still used to a very large extent. In Britain and in the U.S., for instance, driver hand signals were common even during the 1950s.

Some of the early light signals copied the original artificial signals (e.g., turn signals were luminous arms that unfolded from the body of the car, similar to driver and bicyclist arm signals). Because the meanings of abstract signals have to be learned and, after some time, are overlearned and generally understood, engineers hesitate to radically change signals. Changing signals leads to transition problems, with vehicles having different signals for the same message. It also leads to a so-called negative transfer in which one learned reaction has to be extinguished and replaced by another one.

Interestingly, the same signals sometimes have different informal meaning in different countries. Flashing the high beams, for instance, means in some countries, "Here I come, give way," but in other countries it means "Please go ahead, I am waiting." In Sweden, after an overtaking, if the overtaken car has assisted, the overtaking driver expresses appreciation by flashing turn signals right-left. The light-signaling system is used for a number of such local and informal messages. This is one of the consequences of the fact that artificial signals do not have natural, universal meanings. Another reason for the development of such informal signals is that the standard signal system lacks provision for many important messages. For instance, you cannot signal "excuse me," which is a message that solves many problems for walking persons!

Light signals were originally meant for lower levels of ambient illumination, because it was believed that under daylight conditions most vehicle motions and driver manual signals were sufficiently visible. However, gradually it became evident that better signals were also needed under daylight conditions.

Two good illustrations of the importance of light signals during the day are daytime running lamps (DRLs) and center high mounted stop lamps (CHMSLs). DRLs have been shown to result in a significant reduction of certain daylight vehicle collisions (Koornstra et al., 1997), while CHMSLs have been shown to reduce daytime rear end collisions (Kahane and Hertz, 1998). Although the ratio between ambient illumination at night and in daytime can exceed 1:10,000, in practice all signal lights have only single fixed intensities, which are supposed to work in both daylight and night conditions.

Another reason for the development of special motor vehicle signals was the fact that automobiles became covered with roofs and windows. It was no longer possible for other road users to clearly see the driver, or gestures the driver might make. The final reason for the development of new and improved rear lamps was that motor traffic on high speed roads introduced a series of new maneuvers that did not exist earlier, including lane changes, overtakings, and left turns in potential conflict with oncoming traffic.

Originally, the main types of information that needed to be given to the road users behind the vehicle were presence, braking, and intention to turn. In addition, police officers needed to be able to read the rear license plate at night. Consequently, the new rear signals that were developed during the early generations of automobiles were mainly license-plate lamps and tail/position lamps. Later came brake/stop lamps and rear turn signals. It is uncertain to what extent any systematic studies were made in the early phase of rear lighting development. However, efforts were probably made to develop simple, automatically processed rear signals as opposed to more arbitrary signals that required controlled processing.

1.3. The purpose of rear signals

In modern road traffic some of the basic, biological signals listed above (e.g., size and speed) are still valid. For example, most drivers probably understand that trucks will not speed up or slow down as quickly as smaller vehicles. However, a set of new signals was developed to increase safety by reducing the uncertainty of other road users about what would happen in the traffic scene in front of them. There are indications that there is room for improvement in the level of safety provided by present vehicle rear lighting. Rear end crashes have increased steadily. For example, in the U.S. in 1997 there were about 1.9 million rear end crashes, constituting 28% of all crashes (NHTSA, 1998). In comparison, in 1992 there were about 1.5 million rear end crashes, constituting 25% of all crashes (NHTSA, 1993). Furthermore, rear end crashes cause about one third of the crashes responsible for traffic delays. A majority of the rear end crashes occur in daytime, and about two thirds of all rear end crashes involve a lead vehicle that was stopped at the time of impact.

1.3.1. The design of rear signal lamps

There are two main questions to be asked about the design of new signals:

(1) What information is needed by road users behind a vehicle in order to reduce their uncertainty?

(2) How should this information be presented?

To answer the first question fully requires an understanding of many basic problems concerning the driver's task. Although driving an automobile is similar in many ways to walking, a major difference is that driving involves higher speed and energy. Furthermore, the environment being traversed contains fewer natural conditions and signals. The development of a theory of the driver's task in car-following situations is not very far advanced. There are, however, some models that may contribute to the development of more comprehensive theory (e.g., Lee, 1978; van der Horst, 1990).

The second question raises a broad range of issues, from how well signals are detected, to how natural and easy they are to understand. Here, knowledge of basic psychophysical relations concerning suitable stimulus conditions for detection and discrimination is useful. Knowledge of more cognitive processes (e.g., interpretation of symbols) is useful here as well.

The broad outline of the design of rear signals has been influenced by historical circumstances, as we describe in some detail in Section 2 of this report. When nighttime motor traffic increased, the necessity of automobile signal lamps became obvious. The first lamps were adapted from horse-drawn carriages. They were candle and kerosene lamps used more to mark the vehicle than to illuminate the road scene in front of the driver. After marking the front of the vehicle came the issue of marking the rear, which was first accomplished with one license plate lamp combined with a tail lamp. Later, electricity became available in vehicles, but at first it was used only for headlights, and it often was provided only by an add-on device. At first, no lamps were compulsory and various manufacturers developed their own lighting systems, resulting in a large variation of lighting equipment. The first lighting requirements concerned lamps that were not compulsory. However, if a car was equipped with them, they needed to fulfil some rudimentary requirements (e.g., color and area).

In the next phase of development, some basic rear lamps (e.g., tail lamps, license plate lamps, and brake lamps) became compulsory and their characteristics were specified. That was followed by signals that informed and warned other road users about drivers' intentions at long distances. Furthermore, efforts were made to make the signals obvious enough so that they could be also effective in daylight conditions. Successively, brake lamps, turn signals, back up lamps, rear fog lamps, and CHMSLs were introduced.

In this report, we use the term "lamp" when referring to a device and the term "light" when referring to the light emitted by the device. Similarly, we use the following terms, with alternative terms that we consider equivalent in parentheses: tail (presence), brake (stop), and turn (direction indicator). Finally, we use the term yellow for yellow or amber.

Table 1 summarizes the major steps in the development of rear lighting systems. It should be noted that the variations among continents and car makes is considerable.

Table 1. The major steps in the development of rear lighting systems.

Year(s)	Developments
1890-1899	Most cars had no rear lamps.
1900-1911	Many cars did not have any rear lamps. Some cars had one or two kerosene or acetylene lamps with red to the rear and a white lens to the inboard side for license plate lighting. Few cars had electric lamps, dynamo, or accumulators.
1912-1913	Electrical wire harnesses for the total vehicle and vacuum bulbs became available.
1912-1919	Kerosene and acetylene started decreasing and electric lamps started increasing. Headlamps became electric first, and the rear lamps followed. Most cars had one rear lamp (a combined tail and license lamp).
1920-1929	Many cars still had one electric rear lamp (combined tail and license lamp). Some cars had two electric rear lamps (combined tail and license lamps).
1930-1939	Signal lamps started to appear which could indicate stops, turns, or slowing down; they were usually red but sometimes green or yellow.
1939	In the U.S., self-canceling flashing turn signals on each side of the rear were introduced.
1940-1949	In the U.S., most cars on the rear had two tail lamps, two brake lamps, and a license plate lamp. In the U.S., flashing turn signal lamps and a back up lamp were on many cars. In Europe, many cars had one rear position lamp, one brake lamp, semaphore turn signals, and a rear registration plate lamp.
1950-1959	Most cars had two tail lamps, two brake lamps, two turn signals, one or two back up lamps, and one or two license plate lamps. In Europe, many cars still had yellow semaphore turn signals, while in the U.S., most cars had red rear flashing turn signals.
1960-1969	Larger lamps started appearing. One-, two-, and three-compartment lamps. Rear fog lamps were introduced in Europe. ECE regulations started in Europe. FMVSS 108 became the U.S. national regulation.
1970-1979	Zonal values appeared in FMVSS 108. Some harmonization efforts were made regarding signal lamp intensities. Some cars had rear lamps across the total width.
1985	CHMSLs required by FMVSS 108 in the U.S.
1990-1999	CHMSLs and rear fog lamps required by ECE regulations in Europe. Harmonization efforts continued regarding installations and geometric visibility. LED and neon rear lamps introduced in the U.S. and Europe.

1.3.2. Functions of rear signaling systems

Many functions have been added to the rear signaling system during its history, and other functions have been considered but have not yet been implemented. Rear lighting currently offers, or could offer, potentially valuable information such as:

- to attract attention by indicating the presence of the vehicle
- to indicate the width of the vehicle
- to indicate the class or type of vehicle (e.g., heavy truck, passenger car, or motorcycle)
- to indicate the distance between vehicles
- to indicate the rate of closure between vehicles
- to indicate driver intention to brake
- to indicate that the driver has applied the brakes
- to indicate braking force or how rapidly the vehicle is decelerating
- to indicate that the driver intends to bring the vehicle to a full stop
- to indicate that the vehicle has come to a full stop
- to indicate that the driver intends to turn (left or right)
- to indicate that the vehicle is turning (left or right)
- to indicate that the driver has changed the main direction of the movement of the vehicle (from forwards to backing)
- to indicate that the vehicle is parked
- to indicate that the vehicle is in an emergency situation (hazard warning)
- to identify the vehicle (make it possible to read the rear license plate at night)

Rear lighting issues that deserve additional attention include differences between:

- day and night conditions
- clear weather and reduced visibility conditions (e.g., fog, snow)
- single vehicle and vehicle platoon
- new signals and signals in actual traffic
- drivers with normal vision and those with degraded vision

Turn signals and, to some extent brake lamps, indicate the intention of the driver to make a maneuver. Are there other driver intentions that, if signaled, would reduce the uncertainty of the road users behind the vehicle? In general, information that is predictive concerning driver intentions may be useful to following drivers.

1.3.3. Presentation of rear signals

There are a large number of ways in which the types of information listed above can be presented. They all have their advantages and disadvantages. The possibilities include light signals (using intensity, luminance, color, size, form, and temporal pattern), other visual signals, sound signals, or remote activation of in-vehicle displays.

Another important aspect of the rear lighting system is that various signals interact with each other. An optimal system therefore requires that the relationships among the signals be studied. For instance, a higher intensity of one signal will influence optimal intensity of other signals. A larger separation or difference in appearance between signals may reduce such interactions.

2. Common Rear Lamps: Historical Development of Standards and Regulations

Most of the historical documentation of standards and regulations for rear lamps has been in the U.S. and Europe. This is not to say that there have not been important developments in other countries. This report has used information available in the literature, and more has been written about the U.S. and Europe than other parts of the world.

2.1. Organizations

Several different organizations have been involved in developing lighting standards. Comments and explanations are given about some of the more important organizations.

Since the late 1910s, there has been a committee within the Society of Automotive Engineers (SAE) with responsibility for vehicle lighting. At first, this committee jointly worked with an Illuminating Engineering Society (IES) group. Later this became the SAE Lighting Committee. This committee worked with other committees and organizations to develop lighting and signaling standards for automobiles and trucks. As technology changed and improvements were needed, various revisions were made in the original lighting standards which were created in 1918. Many of the SAE lighting standards have been incorporated in whole or in part into U.S. and Canadian regulations.

In the U.S., the SAE Lighting Committee has had a leading role in the development of lighting standards. The SAE Lighting Committee has always been of the opinion that proposed values of intensities, colors, positions, areas, etc. (often based on research results) must be observed and evaluated by a group of experts in real life situations before values become part of a standard. Therefore, the committee has had sessions at its meetings where various lighting proposals are observed in real situations and evaluated by the committee members, normally 80-100 professionals in lighting and safety representing industry, governments, academia, and users. A criterion of 80% acceptance (e.g., minimum intensity to reach an acceptable visibility, of maximum intensity not to cause too much glare) has over the years proven to be a good level for requirements that have entered the standards (Meese, 1983).

The IES was founded in 1906, one year after SAE. A joint committee of the two societies was responsible for publishing the first automobile lighting standard in 1918, revised in 1922. At that time, this standard focused exclusively on headlamps with only one beam (Meese, 1983). The first SAE-IES standard for rear lamps was adopted in 1922 for a tail lamp, but it specified light for the license plate and stated that the red light to the rear should be visible for 500 ft [152 m] (SAE, 1925). Gradually the functions (e.g., introduction of brake lamps) and the requirements (e.g., intensities) were upgraded as new materials and technologies permitted.

The International Organization for Standardization (ISO) consists of the national standards organizations in many countries around the world, for example, the American National Standards Institute (ANSI) in the U.S., the Canadian Standards Association (CSA) in Canada, and the British Standards Institute (BSI) in England. ISO establishes voluntary industrial standards to be used for manufactured products in many different fields, including automotive lighting.

The Commission Internationale de l'Eclairage (International Commission on Illumination; CIE) is oriented towards basic lighting research. It covers all types of illumination including stage, photographic, building, airport, naval, fixed roadway, and automotive. CIE had a special committee on vehicle lighting (TC 4.7) that had regular meetings for several years.

The Groupe de Travail-Bruxelles 1952 (GTB) is an international lighting group of experts from light-source, lighting-device, and vehicle manufacturers. GTB was established jointly by ISO and CIE in 1952. GTB serves as a technical advisory group to the Groupe de Rapporteurs Eclairage (Group of Experts-Lighting; GRE). GTB, in which industry is well represented, has done the technical work and technical preparation for most of the Economic Commission for Europe (ECE) lighting regulations that were adopted by GRE and WP29 (Working Party 29 on Construction of Vehicles). WP29, has a number of expert groups specialized in various vehicle areas preparing issues for them. GRE (Groupe de Rapporteurs Eclairage) is the special group on lighting.

Finished regulations are published by the ECE, which is a subsidiary to the United Nations. The European Community or European Union (EU) became a party to the 1958 agreement of the ECE in March 1998. The European Union publishes directives on vehicle regulations. These directives are normally based on the ECE regulations. However, contrary to the ECE regulations the EU directives are compulsory.

Another European lighting group that is involved in developing standards is CEN (Commission European Normalisation). CEN is the standardization organization within the EU. As far as we know, they have not yet worked with any vehicle lighting questions.

2.2. Government lighting regulations

Lighting started on vehicles before there were any national or international government regulations and industry standards in either the U.S. or Europe. After a few years, in the mid 1910s in the U.S., there were some state lighting regulations and SAE/IES industry lighting standards. The number of states adopting lighting regulations increased, and so did the number of industry lighting standards. In the early 1920s, in Europe, there were some national lighting regulations. This situation existed in Europe until after World War II when, under the UN organization, ECE regulations were established. They created some uniform international lighting regulations (adopted by most European countries, but not by the U.S.).

The U.S. continued with state lighting regulations until the U.S. federal government passed the Motor Vehicle Safety Act in 1966. The U.S. National Highway Traffic Safety Administration (NHTSA) was created in 1968. Within a few years, U.S. federal government regulations were established for lighting, which were originally, in most cases, the existing SAE lighting standards.

The U.S. government has a self-certification approval process, meaning that the manufacturer does what is necessary to meet the requirements. The manufacturer must test and satisfy the requirements and show continuing "due care" that the manufactured products will also meet the requirements.

The ECE regulations have a type-approval certification process. A manufacturer must submit products to a designated national testing laboratory. If the submitted product meets the requirements in the regulation, then the product is type approved. Approval numbers are granted and the manufacturer can make the product with the approval number legibly included on the product.

These two very different systems still exist in 1999. They both have their advantages and disadvantages. The type-approval process requires the manufacturer to submit parts to a national laboratory for testing. The manufactured products only have to meet the COP (conformity of production) requirements, which are considerably less stringent than the type-approval requirements.

Europe, soon after the UN established the ECE system, started adopting lighting regulations. A summary of those relevant to this report is included in Table 2. NHTSA incorporated into FMVSS 108 (Federal Motor Vehicle Safety Standard) several SAE lighting standards, including several relevant to rear lighting (see Table 3). There was not an SAE standard for rear fog lamps until SAE J1319 (August 1987). There is not an SAE standard for installation of lighting devices. Some of the installation information is included in each individual SAE standard, and some is included in parts of FMVSS 108.

Table 2. ECE regulations relevant to rear lighting.

ECE Regulation number	Subject	Date established
R4	License plate lamps	1964
R6	Turn signal lamps	1967
R7	Brake/tail lamps	1967
R23	Back up lamps	1971
R38	Rear fog lamps	1978
R48	Installation of lighting devices on a vehicle	1981

Table 3. SAE standards relevant to rear lighting that were incorporated in 1970 into FMVSS 108.

SAE standard number, date	Subject
J585c, June 1966	Tail lamps
J586b, June 1966	Brake lamps
J588d, June 1966	Turn signal lamps
J593c, February 1968	Back up lamps
J587d, March 1969	License plate lamps

2.3. General development

The first motor vehicles did not have any lighting. Several vehicles in museums and in photographs up to 1910 show various new car models without any lighting.

Drach (1993) describes the development of automobile lighting primarily in Europe and especially in Germany. Because the automobiles from 1886 up until about 1900 were very similar to horse carriages with engines, they were equipped with lamps designed for use on horse carriages. The speeds of the first cars were not more than 20 km/h, and they did not really need any illumination, just markings to make them visible to other road users. Consequently, those first lamps were candle lamps, which were just moved from the horse carriage to the car. There were normally no lamps in the rear. Some early vehicles, 1895-1899, had original equipment lighting installations that could be purchased with the vehicle when it was ordered.

The devices often had openings to the side to mark the vehicle and a small red opening to the rear, more to make it possible for the driver to see that the lamp was lighted than to mark the rear of the vehicle. At the end of the century, the speeds of motor vehicles increased and the candle lamps were no longer acceptable. Lamps especially made for motorized vehicles started to be available. Oil (kerosene) lamps and the first acetylene lamps were introduced. During the first years of the century, the front lamps were often acetylene and the rear lamps were kerosene, which were often transformed bicycle lamps intended for license plate illumination.

The first lamp device was installed on the front of the vehicle. However, it could not be considered a real headlamp. It was more of a position lamp or a presence lamp. Next, one or two kerosene side lamps (really front position or front parking lamps) were installed near the windshield or the dash. Card (1987) mentions an electric side lamp in 1901, which had its own accumulator (battery). There was not a vehicle recharging system so the life of the light was not very long.

Headlamps went through a transition using acetylene. Most headlamps were acetylene by 1906 (Horseless Carriage Gazette, 1961). Retrofit burners were made available to change over the headlamps and side lamps to acetylene. During this time, the first complete acetylene automobile lighting systems appeared. That is to say, a central acetylene container provided gas to the front as well as the rear lamps. Electric headlamps started in limited usage in 1908. By 1912, most headlamps were electric. However, acetylene headlamps continued to be used on some vehicles into the 1920s.

The first rear lamp, a red presence lamp, was kerosene because there was no vehicle wire harness or electrical system. At this time, the early lighting on the rear of the vehicle was primarily to illuminate the license plate, and only secondarily to provide an indication of the presence of a vehicle ahead (tail lamp). One lamp supplier made a square tail lamp assembly, in which a red lens emitted light toward the rear, a white lens emitted light (in an inboard direction) toward the right to illuminate the license plate, and a green lens emitted light (in an outboard direction) toward the left (Horseless Carriage Gazette, 1961). This followed the marine boating convention for having different colored lights on each side of a ship. Now two rear lamps showed up for the first time. The main reason was probably that the license plate needed illumination from two sides. Since the same lamps were used on each side, this resulted in two instead of one tail lamp.

Figure 1 illustrates a typical rear lamp of the first generation. It is a kerosene burner with one white light opening to the inside illuminating the license plate, one red light opening to the rear for the tail light, and (in this specific case) one green light opening to the outside indicating the left side of the vehicle.

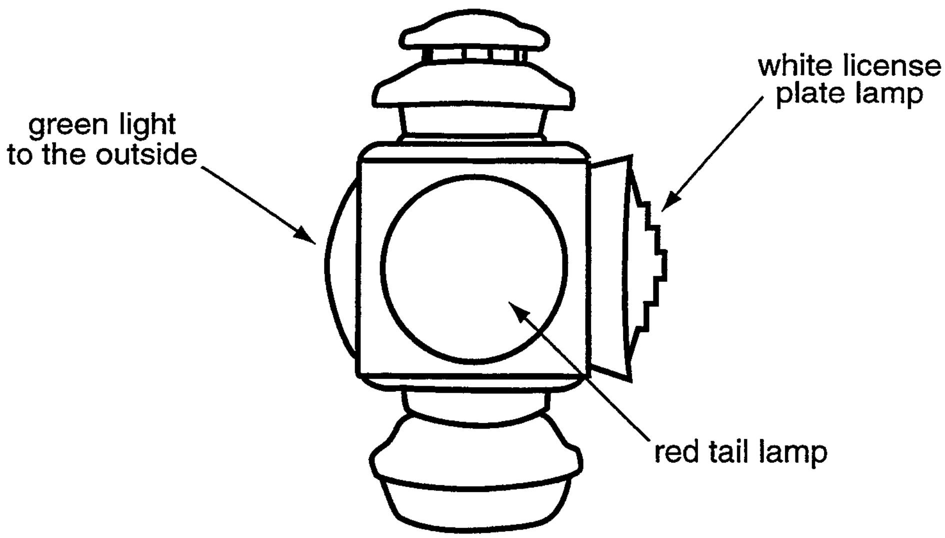

Figure 1. A schematic representation of a 1911 Hupmobile kerosene rear lamp with red, green, and white lenses (Henry Ford Museum, Dearborn, Michigan).

Another method used for the license/rear lamp was to make an opening to the rear in the white license plate lamp housing and cover the opening with a red or red/yellow glass. One method in the 1910s used to illuminate the license plate was by means of a transparent display, illuminated from the rear by means of a paraffin lamp (Hella, 1999). However, most rear signal lamps continued with kerosene until electric bulbs were used. By 1920, the majority of vehicles had electric powered rear lamps.

Between 1905 and1915, several lighting suppliers made hybrid installations of kerosene and electric to obtain a stop lamp function (Frye, 1964). An electric socket was put into the kerosene rear lamp assembly with a wire harness. This was before two-filament bulbs were invented. When the vehicle wire harness became available, most cars used all electric lighting (Horseless Carriage Gazette, 1961).

In Europe, the first electrified automobile lamps were introduced after 1906, when a filament bulb was produced that could withstand the jolts caused by driving on the still unpaved streets. These bulbs were used mainly in side lamps and rear lamps and were powered by batteries. The first vehicle dynamo or generator was patented in Germany in 1912 (Hella, 1999).

Lighting regulations and standards were minimal, if they existed at all. According to Abbott (1909) (as cited in Lewerenz, 1965), California Automobile Law placed more emphasis on illumination for the license plate than light for a following driver:

> Every motor vehicle, while in use on a public highway, shall be...so constructed as to exhibit, during the period from one hour after sunset to one hour before sunrise, two lamps showing white lights visible within a reasonable distance in the direction towards which such vehicle is proceeding, showing the registered number of the vehicle in separate Arabic numerals, not less than one inch in height and each stroke to be not less than one quarter of an inch in width, and also a red light visible in the reverse direction (Lewerenz, 1965).

The transition phase from kerosene, to acetylene, to electric lamps occurred over several years. The following interesting comment about this transition was made in 1912:

> Electric lighting today [1912] is past the experimental stage. Manufacturers of every accessory pertaining to electric lighting such as batteries, lamps, reflectors, bulbs, even the wiring and switches, have perfected their construction to such an extent that there is hardly any improvement to be had that is not embodied in the different electric lighting accessories that we offer on the following pages (American Auto Supply Co.; New York and Chicago) (Post, 1970).

The first vehicle-wide harness was used in the industry in 1912 (Johnston, 1996). Along with the introduction of vacuum bulbs, this allowed increasing numbers of electric rear lamps to be installed on vehicles. Finch (1970) describes an add-on electrical rear lighting device, which was available in the U.S. in 1912. It must have been far ahead of its time, because it provided a red tail lamp, a green brake lamp (actuated by the application of the car's brakes), a white license plate lamp, and a pair of white turn signal lamps. These types of lamps did not come into regular use until more than twenty years later. This seems to be the birth of a rear lighting system.

After World War I, most cars were equipped with a vehicle-wide electrical system, which was also used for the lighting system. After that, the side lamps, the front position, and the parking lamps were placed in the vicinity of the headlights. The first electrical side lamps (1912) had a 10 W filament bulb with a strong lens. The electrical development was initially hampered by the fragility of the old carbon filament lamp. The new vacuum bulbs did not appear until 1913. Then production of electrically powered vehicle lamps started (Finch, 1970).

The economic development after World War I was quicker in the U.S. than in Europe. Automobile lighting also developed to a larger extent and more quickly in the U.S. than in Europe (Maurer, 1980).

Because of concern about the increasing number of accidents, the British Parliament in the late 1920s enacted laws to require vehicles to have two headlamps, two side lamps (front position lamps), and one license lamp (which also was a combined brake/tail lamp) (Card, 1987).

Germany regulated lighting equipment for automobiles for the first time in 1923. In 1930, the regulation was revised and improved for new vehicles (Licht und Lampe, 1930). One problem at that time was that some vehicles still had acetylene or even oil as the energy source for vehicle lighting. That is one of the reasons why rear position lamps were still only optional. Also, it was felt there was enough marking of the vehicle with retroreflectors on the rear. However, rear license plate illumination seems to have been compulsory.

The first electric tail lamp in Europe, with a built-in red or orange brake light, appeared in the mid 1920s. It was one lamp placed on the left side of the rear of the vehicle (right-hand traffic). In 1926, a combined tail/brake/license plate lamp was produced. The tail lamp (bottom part) could have a text (e.g., Opel) or a sign (4—indicating that the car was equipped with four-wheel brakes). The brake lamp (top part) had the text STOP. The same type of rear lamps continued to be produced also during the 1930s (Hella, 1999).

Internationally, the League of Nations had a meeting in 1926 in Paris and agreed on two relevant conventions, one on Road Traffic (No. 2220) and one on Motor Traffic (No. 2505) (League of Nations, 1926). These two conventions were ratified a few years later by a large number of countries. These conventions include the following concerning rear lighting:

- From sunset and during the night every motor vehicle must be equipped with a red light at the rear.
- Every motor vehicle must carry a registration plate that at the rear must be illuminated when it cannot be read in daylight illumination.

However, initially in 1923 and again in 1930, Germany was of another opinion concerning the color, and specified that the tail lamps should be orange. The reason for this choice of color was that Germany reserved the red light for railway signals! The color orange was not specified in any other way, so we do not know exactly what mixture of red and yellow was intended.

In 1932, brake lamps and turn signals were still optional in Germany, while the tail lamp was mandatory. However, if a brake lamp was used it had to be red. If turn signals were used, they had to be in the form of an arm unfolding from the body of the car visible both from the front and rear, and the light had to be orange (illuminated from the inside of the arm). White or slightly yellow reversing lamps were allowed. Their light had to be angled down so that it reached the ground not more than 10 m from the vehicle. It was required that reversing lamps could be turned on only when the transmission was in reverse gear.

In 1935, Germany prescribed that tail lamps and brake lamps must be red. In Germany in the late 1930s, the first plastics were introduced as lens materials (Hella, 1999). Before 1940, all lenses for lighting devices in the U.S. were made from glass. The first use of yellow and red acrylic was in 1940 for truck clearance, marker, and identification lamp lenses (Fisher and Bostick, 1968). Rapidly over the next several years, the use of plastic for lenses, increased greatly both in the U.S. and in Europe.

Initially, the brake lamp used the same 21 cp single-filament bulb that was being used in headlamps. In the late 1930s and early 1940s, two instead of one rear tail/brake lamps were introduced in the U.S. together with the streamlined all-metal bodies. When the turn signals were integrated into the same housing by means of a two-filament bulb, the turn signal was also red because it used the same lens as the tail lamps (Hitzemeyer et al., 1977).

In 1935, British regulations were introduced for turn signals and brake lamps (Minister of Transport, 1935). From that year it was allowed to fit vehicles with an internally illuminated semaphore arm indicator. The arm had to be illuminated with a steady yellow light, and it had to be visible from the front and the rear. When in operation, it had to alter the outline of the vehicle by 6 in (15 cm) measured horizontally. This regulation was valid until 1954.

After World War II, there was a boom of motor traffic, both in the U.S. and in Europe. The second convention on road traffic was held in 1949 in Geneva (now under the auspices of the United Nations) (UN, 1950). Here started many of the present automobile lighting requirements, including the following:

- at least one red position lamp on the rear
- license plate lamp(s)
- at least one brake lamp on the rear (red or yellow)
- when there are turn signal lamps (not mandated but allowed), any of the following were allowed:
    - semaphore arm (yellow) on each side
    - flashing turn signal (yellow) on each side
    - flashing turn signal
        - on the front on each side (yellow or white)
        - on the rear on each side (yellow or red).

In 1949, the British car manufacturers adopted, with some modification, a 1947 SAE tail lamp standard. This stated that, within 15° left and 15° right and 15° up from the optical axis, the red light shall have an intensity of at least 0.25 cd. In a horizontal direction, 30° left to 30° right, there shall be an intensity of at least 0.10 cd (Moore, 1952).

In 1951, ten years before any statutory requirements, the first flashing turn signals were introduced in Europe. In 1957, there was a combined tail lamp, retroreflector, and a signal lamp in which the light was focused and distributed by the lens only, without any reflector (Hella, 1999).

In 1952, the British legislation required vehicles to have a red light to the rear visible from "a reasonable distance." The red light had to be placed on the rear of the vehicle, either on the vehicle centerline or on the right side of the vehicle (for left-hand traffic). The red light could not be more than 42 in (107 cm) from the ground (unless a red reflector or a white surface was carried at or below that height). There was no official specification of the size, shape, or power of rear lamps (Moore, 1952).

In the 1950s came the requirement in Europe that there should be two tail lamps. From 1954, all new cars had to have type-approved brake lamps. From 1956, all new cars had to be equipped with flashing turn signals instead of the previous semaphore arm. Old cars had to be retrofitted with flashing turn signals after 1961. From the beginning of the 1960s, the rear lamps started to be more multifunctional and more integrated with the car bodywork. The flashing turn signals, the reversing lamps, and the rear fog lamps were integrated into one combined rear lamp housing (Hella, 1999). Rather than having one rear lamp model that could be used on many vehicles, there was a rear lamp model for every vehicle model.

Road traffic increased and lighting technology improved in the 1950s and 1960s. A third major convention on road traffic was held in Vienna in 1968 (UN, 1969). There most of the remaining vehicle lighting requirements were agreed on and several changes were made regarding the number of lighting devices that were required on motor vehicles, including the following:

- even number (not one) red position lamps on the rear
- license plate lamp(s)
- two red brake lamps (yellow not allowed any longer)
- flashing yellow turn signals required (could be on the side, or on the front and the rear)
- reversing lamp allowed but not required.

There have been a number of amendments and revisions to the 1968 UN agreements.

2.4. Tail, rear position, and parking lamps

The first indications of one license/tail lamps and one tail lamp in pictures and from observations of old collector cars are in about 1900-1905. These were observed on European cars at the Heritage Car Museum in Warwick, England; on U.S. cars at the Henry Ford Museum in Greenfield Village in Dearborn, Michigan; and in several photographs in the Horseless Carriage Gazette (a collector magazine of mostly U.S. manufactured vehicles). These first lamps were kerosene lamps. After 1912, most tail lamp installations were electric, and used a 2 cp bulb (Kebler, 1912).

By 1916, the SAE/IES committee with responsibility for lighting had determined a vocabulary listing of lighting including head lamp, side lamp, and tail lamp (SAE, 1916).

The first SAE standardization activity for tail lamps was in 1919 to specify a common dimensional size of 3 in (7.6 cm) in diameter with tolerances of plus 1/32 in (0.8 mm) and minus 1/64 in (0.4 mm) (SAE, 1920). The second activity was in 1920 (SAE, 1925) when the tolerances were revised to plus 0 and minus 1/32 in (0.8 mm).

A photometric standard was adopted in 1923 (SAE, 1925) for a 2 cp electric tail lamp. The requirements were as follows:

> The illumination as measured shall not be less than 0.5 foot-candles [5.4 lux] at any point on the registration number-plate (white light). The ratio of maximum to minimum illumination shall not exceed 30. No lamp shall be considered acceptable unless it conforms with the requirements for measured illumination and the ruby (red) light is visible for at least 500 ft [152 m].

These same requirements were in IES (1923). Therefore, for at least a few years there was good cooperation between the SAE and the IES regarding automotive lighting.

In 1927, the SAE Lighting Committee adopted a revised standard for tail lamps (SAE, 1928). This maintained the 500 ft (152 m) visibility distance but also stated that tail lamps shall emit a ruby (red) light with a minimum of 0.10 cd at the H-V point; a minimum of 0.05 cd within a 30° conical angle of the H-V point; and a maximum of 5 cd anywhere in the pattern. This was with a 2 cp bulb. Figure 2 illustrates the photometric requirements for the tail lamp in 1928; before then the requirement was only that the signal had to be visible at 500 ft (152 m). These photometric requirements for the tail lamp did not change from 1927 through 1946.

Magdsick (1928) provided a good summary of the lighting laws in the U.S. (These laws did not yet reflect the SAE standard of one year earlier, including some lighting intensities.) Ten states required rear lamps (tail and license plate lamps); seventeen states required the tail lamp to be visible at 500 ft (152 m); one state required visibility at 300 ft (91 m); three states required visibility at 200 ft (61 m); and five states required visibility at 100 ft (30 m). In forty states the light from the rear lamp had to be red, in four states it had to be either red or yellow, and in one state, it had to be either red or green. The states also had requirements for the license lamps (see Section 2.5 below).

Requirements in Germany in 1930 for parking at night or in thick fog prescribed the front parking lamps or the low beam headlights on the front, and license plate lamp in the rear (Licht und Lampe, 1930). These lamps had to be turned on if the street lighting where the car was parked did not provide enough illumination for visibility. The allowed light sources for parking lamps were as follows:

- electrical filament bulb of 2-10 W
- electrical filament bulb of 10-35 W, if it is only using half of the original voltage
- acetylene lamps burning 5-10 liters per hour
- lamps burning on oil or candles.

The German regulation was amended in 1932 (Licht und Lampe, 1932). Now the German requirements were harmonized with the international agreement on road traffic from 1926. This meant that beginning in 1933 a rear position lamp was mandatory, and had to be red and not larger than 20 cm^2. Lenses, reflectors, and other means to make the lamp more intense were not allowed. The reason for limiting the surface and intensity of the rear lamp was, again, the priority given to the railways. The automobile rear lights must not cause any confusion with the railway signals.

In 1947, SAE revised the tail lamp photometric requirements (SAE, 1949). The intensity at H-V was increased 150% (from 0.10 cd to 0.25 cd). The 0.25 cd was also required at all points within 15° left to 15° right and 15° up. From 30° left to 30° right, along the horizontal line, the required intensity was 0.10 cd. The maximum above the horizontal line was still 5 cd. Figure 3 illustrates the photometric requirements for a tail lamp in 1947.

In 1953, the SAE increased the allowed maximum intensity for the tail lamps from 5 cd to 10 cd (SAE, 1953). The minimum was still 0.25 cd.

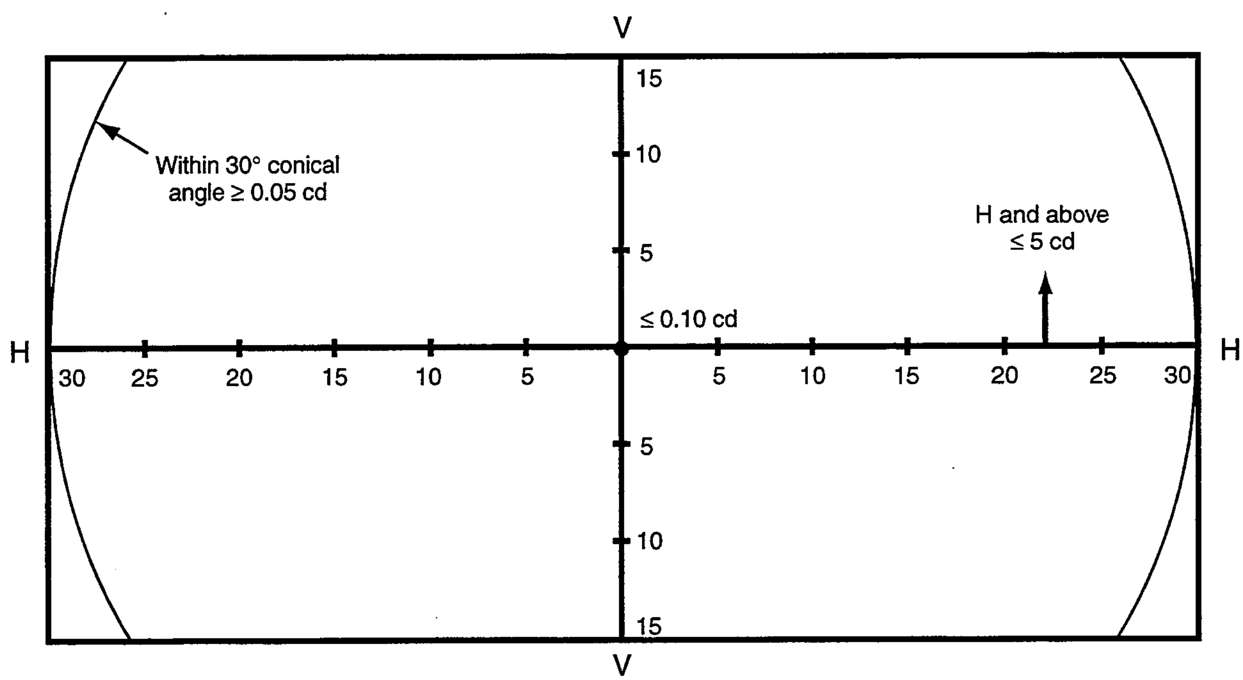

Figure 2. SAE tail lamp photometric requirements in 1928. There were three requirements: minimum 0.10 cd at H-V, minimum 0.05 cd within 30° conical angle, and maximum 5 cd at H and above.

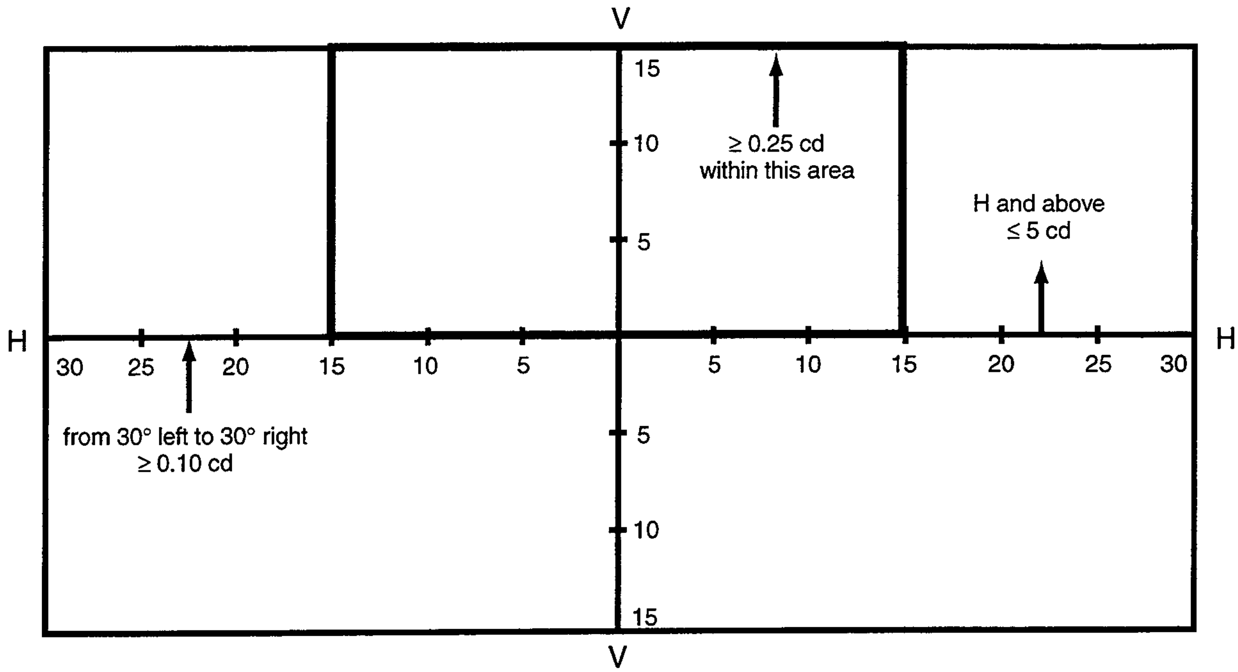

Figure 3. SAE tail lamp photometric requirements in 1947.

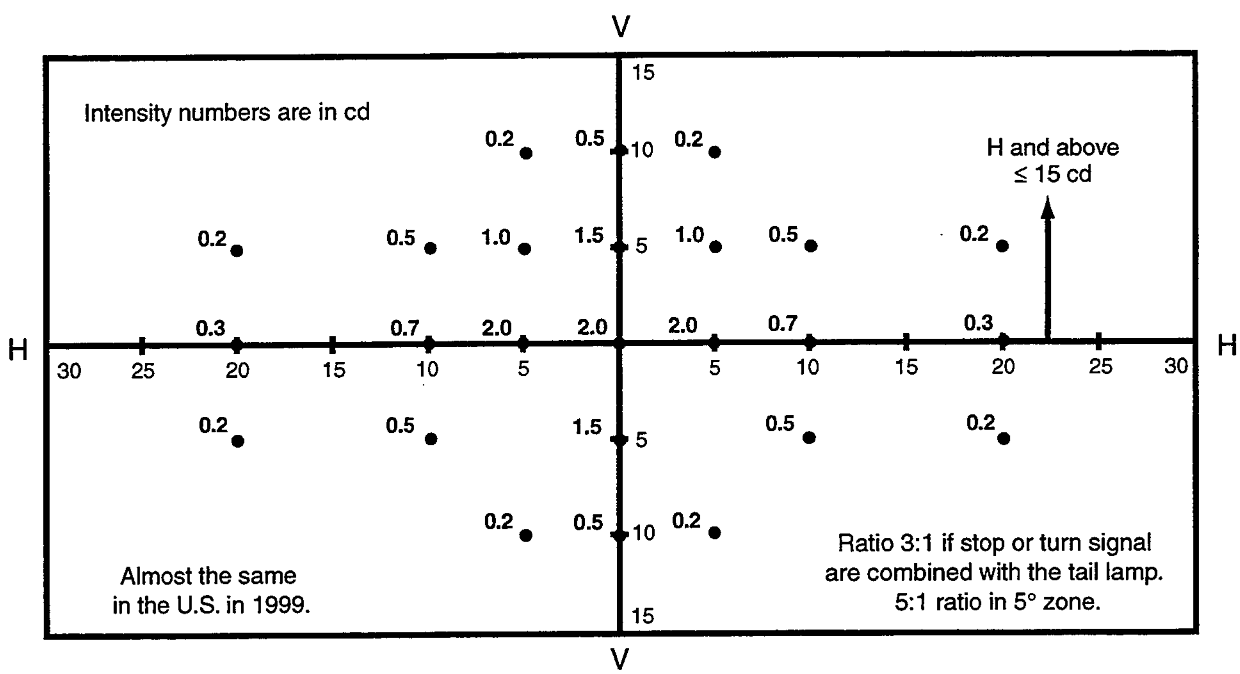

Figure 4. SAE tail lamp photometric requirements in 1955. Current requirements are virtually the same.

In 1954, the changes regarding photometric intensity requirements for the other signal lamps were also applied to the tail lamp (SAE, 1954). Intensities were increased and the photometric grid was established (20° left to 20° right, and 10° down to 10° up). The minimum at H-V was 1.5 cd and the maximum for the tail lamp, above the horizontal line, was 15 cd. Also, there was a requirement that when the tail lamp was combined with some other signal (brake or red rear turn signal) the intensity for the test points above the horizontal must be at least three times greater for the brake or red rear turn lamp than for the tail lamp.

In Britain, the Road Vehicles Lighting regulations of 1954 and 1958 provided the legal requirements for rear lighting in Britain. It was now compulsory to fit two rear lamps to all cars. Every obligatory rear lamp, if circular, had to have an illuminated area of not less than 2 in (5 cm) in diameter, and of such a shape that a circle of 1 in (2.5 cm) diameter might be inscribed therein. From 1959, the intensities in the center of the rear light were a minimum of 0.25 cd (preferably 1.5 cd), and had a specified light distribution (Minister of Transport and Civil Aviation, 1954 and 1958). The higher intensity level was similar to the 1954 SAE standard.

In 1955, the tail lamp photometric requirements in the U.S. were revised to 2 cd minimum at H-V (SAE, 1955). (This minimum requirement has existed to the present.) The ratio requirement was revised slightly; the three times ratio (see above) still existed for all test points above the horizontal, but now for the 5° zone the ratio of brake lamp or red rear turn signal lamp had to be at least five times the tail lamp. Figure 4 illustrates these photometric requirements, which are almost the same as in the current FMVSS 108 (Office of the Federal Register, 1998).

For tail lamps in 1960, neither multi-compartment nor multiple-lamp arrangements had yet been considered (SAE, 1961).

The SAE in 1967 created the photometric requirements for multicompartments (see Table 4) that have existed, essentially unchanged, to the present (SAE, 1968). The reasons for introducing compartments were probably mainly to achieve a larger area without having to make the lamp very deep. As a fringe benefit of multi-compartment lamps, redundancy was also obtained.

Table 4. SAE (1968) tail lamp photometric requirements for multicompartments (cd).

Aspect	Number of compartments		
	1	2	3
H-V minimum	2.0	3.5	5.0
Maximum	15	20	25

Because in 1967 all signal lamps used incandescent tungsten filament bulbs, the multi-compartment designation was based solely on the number of separately lighted areas (bulbs) in a lighting device. There was an increase in the intensity required or permitted at H-V as the number of compartments increased. However, this increase was not proportional to the expected increase in area, and thus the intensity increase did not keep the luminance constant. The requirements for compartment lamps have continued to cause problems for new technology lamps (LEDs) in the 1990s. Even now there is an SAE task force working on this situation, and NHTSA has recently issued a notice of proposed rulemaking to change the compartment designations for signal lamps.

Under UN organization, several ECE regulations were prepared. The ECE R7 for brake and position lamps was adopted and put into practice in 1967 (Cole et al., 1977). The ECE R7 photometric requirements for a rear position lamp in 1967 at H-V were 2 cd minimum and 12 cd maximum. The photometric distribution extended from 20° left to 20° right and from 10° down to 10° up. There also was a geometric visibility requirement of 0.05 cd from 45° left to 45° right and from 15° down to 15° up. (Geometric visibility means the angular field in which all or a portion of the lamp surface is visible.) Except for the geometric visibility requirement, this is similar to the photometric requirements for a tail lamp in the U.S.

In 1968, NHTSA was formed in the U.S. Department of Transportation. NHTSA established the Federal Motor Vehicle Safety Standard FMVSS 108 for lighting. FMVSS 108 incorporated SAE J585c, June 1966, for tail lamps. From this time on, the regulatory requirements for tail lamps in the U.S. were FMVSS 108 and not state and SAE standards. The photometric requirements introduced into FMVSS 108 were similar to those shown in Figure 4.

FMVSS 108 in 1973 created the zonal photometric requirements (Office of the Federal Register, 1973). This meant the lamp did not have to meet each individual test point requirement if the sum of the test points in a zone met the zonal total photometric requirement. For example, for a one-compartment tail lamp the requirements within 5° of H-V are those listed in Table 5. Later a note was added that the individual test points could be 60% of the individual test point requirement, as long as the zonal total was met.

The next change in FMVSS 108 for tail lamp requirements was in 1980, when the maximum value for a single-compartment lamp was increased to 18 cd. No change was made in the maximum values for two or three-compartment tail lamps (Office of the Federal Register, 1980). This revision was made because many one-compartment rear lamps were direct optics lamps (tail, brake, and turn signal combined and not employing a reflector). In such a lamp assembly, the optical design was determined by the photometric requirements for the brake and turn signal. When making a good brake or turn signal, it resulted in a tail lamp that was very close to the existing maximum of 15 cd. The U.S. government and industry agreed it was better to raise the tail lamp maximum rather than decrease the brake/turn signal minimum.

Table 5. Zonal photometric requirements for a one-compartment tail lamp in FMVSS 108, 1973.

Test point location	Test point minimum intensity requirement (cd)	Zonal total minimum requirement (cd)
5U-V	1.8	9.6
H-5L	2.0	
H-V	2.0	
H-5R	2.0	
5D-V	1.8	

SAE in 1986 made a change that was not incorporated into FMVSS 108 (SAE J585, March 1986). Two different tables—photometric design guidelines and photometric requirements—were created. This was similar to the ECE type-approval and COP requirements (see Section 2.2.)

SAE J585, December 1991, contains the tail lamp requirements for passenger cars. A new standard (SAE J2040, June 1991) was created for tail lamps on heavy-duty vehicles which only has photometric requirements for one-compartment lamps because most heavy-duty vehicles only have one-compartment lamps. Several of the SAE standards have been divided into one version for passenger vehicles and one version for heavy-duty vehicles.

The existing U.S. FMVSS 108 tail lamp requirements in 1999 (Office of the Federal Register, 1998) are almost the same as those originally adopted in 1968. The only significant change has been an increase in the allowed maximum for a one-compartment lamp. The existing European ECE R7 rear position lamp requirements in 1999 (ECE R7; 1998) are also almost the same as those originally enforced in 1967 except the minimum requirement is now 4 cd at H-V (the maximum is still 12 cd), and some changes have occurred in the geometric visibility requirements to make the field of view larger, but the 0.05 cd intensity value, for geometric visibility, is the same.

2.5. License plate lamps

License plate lamps were the first compulsory rear lamps. The first photometric requirements in 1923 were intermixed with those for a tail lamp described above in Section 2.4, because the tail lamp and license plate lamp lighting functions were combined in one assembly (SAE, 1925).

In 1927, the SAE revised the license plate lamp requirements (SAE, 1928). The previously mentioned requirements still existed (0.5 ft-c [5.4 lx] and the maximum ratio of 30), but now for the first time the 8° incident angle requirement was specified and the light cutoff of illumination was extended for 1.5 in (3.8 cm) beyond the farthest edge of the plate from the lamp.

Magdsick (1928) summarized the existing state laws. Legibility or visibility of the license plate was specified at a distance of 50 ft (15 m) in twenty states, 100 ft (30 m) in two states, 60 ft (18 m) in five states, and 25 ft (7.6 m) in three states. In eight other states, the only requirement was illumination of the plate (nothing else specified).

SAE (1939) included the first separate standard for license plate lamps. It contained the illumination levels and the ratio requirement previously mentioned.

By the time NHTSA incorporated license plate lamps into FMVSS 108 in 1968 (SAE J587d, March 1969) the lighting and mounting requirements were as follows:

- Angle between the plane of the license plate and the plane on which the vehicle stands will not exceed 90° ± 15°.
- Light rays shall reach all portions of a plane at least 1 in (2.5 cm) ahead of the actual license plate measured perpendicular to the plane of the plate.
- License plate lamps shall be mounted so as to illuminate the license plate from the top or sides.
- When a single license plate lamp is used, the incident light shall not make an angle of less than 8° to the plane of the license plate.
- When two or more license plate lamps are used, the minimum 8° incident light angle shall apply only to that portion of the license plate that each particular lamp is to illuminate.
- Illumination on each of the eight designated test locations shall be at least 0.75 ft-c [8.1 lx].
- Ratio of maximum to minimum illumination shall not exceed 20:1 for the 6 in by 12 in (15 cm by 30 cm) plate for passenger cars and 15:1 for the 4 in by 7 in (10 cm by 18 cm) plate for motorcycles. Average of the two highest and the two lowest illumination values at the eight test locations shall be taken as the maximum and minimum, respectively.

Out of all the above requirements for license plate lamps, the only one that does not exist in 1999 is the one requiring the license plate lamp to be mounted on the top or sides (Office of the Federal Register, 1998). This allows a license plate lamp to be below the license plate, which had been prohibited for a few years.

The sizes of European license plates are different from those in the U.S. There are illumination requirements in the ECE Regulation 4 (1977) that differ from those in the U.S. (These same requirements existed when ECE R4 was first introduced in 1964.) The European requirements are as follows:

- There are twelve designated test point locations.
- Luminance at the test points shall be at least 2.5 cd/m^2.

- Difference in illumination values between two test locations shall not exceed twice the value of the minimum reading at any test location.

2.6. Brake/stop lamps

The first mention of a "STOP" sign, exposed when the brakes were applied and illuminated at night, was made in 1905 by the French and British for an aftermarket vehicle installation (Fisher and Bostick, 1968). (Nothing is said to indicate this was an electric lamp; it is earlier than most other references for electric lamps.) This was made available to "diminish street accidents."

Brake lamps first appeared as a combined assembly with a tail lamp. While kerosene tail lamps were still being used, lamp manufacturers installed an electric light source to give additional illumination (Frye, 1964). This extra electric light source was connected to the brake pedal to give an indication that the vehicle was slowing down or stopping.

Brake lamps offered as original equipment by a vehicle manufacturer appeared about 1916 (General Motors, 1965). There is a 1916 Apperson at the Henry Ford Museum with a brake lamp with the word STOP in the lens. Figure 5 shows a rear lamp from a 1930 Auburn.

Falge and Johnson (1923) provide a good review article of brake and other signal lamps in use in the U.S. at that time. They indicated that fourteen automobile companies installed signal lamps as initial equipment and a number of states passed laws making the use of some form of mechanical or electrical signal compulsory. The early installation of a brake lamp was only one per vehicle, and it was mounted on the left rear fender. Several signal lamp applications were described: STOP lamps with the text letters actually included in the lens; brake-tail combined lamps; SLOW and STOP combined lamps, where SLOW indicated that the clutch or brake was depressed and STOP replaced SLOW when both pedals were depressed; a lamp based on the accelerator position (when the accelerator was being pressed a green light would be lighted and when the accelerator was not pressed a red light would appear); and a combined brake/turn signal lamp with pointed arrows indicating the direction of a turn.

The first mention of a telltale for a signal lamp appears in Falge and Johnson (1923). Because of the newness of signal lamps, it was felt the driver needed to be assured every time that the signal lamps were working correctly. "In recognition of the importance of an indicator, the Connecticut law now [1923] requires that a device of this kind be provided with electrically lighted rear signals" (Falge and Johnson, 1923, p. 476).

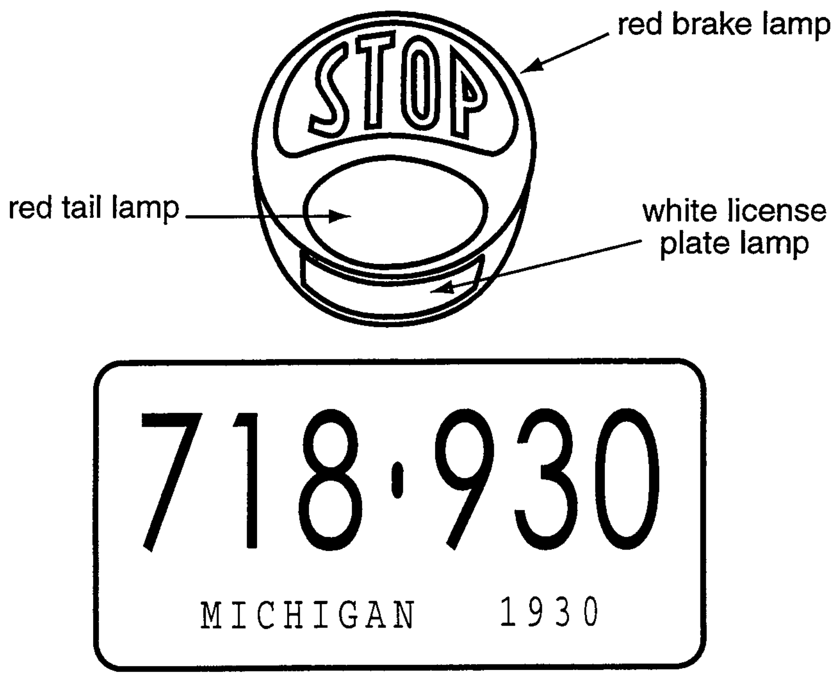

Figure 5. A schematic representation of a 1930 Auburn rear lamp with the text STOP in the lens of the brake lamp (Henry Ford Museum, Dearborn, Michigan).

A telltale was not required for acetylene or kerosene rear lamps, only with this new "unreliable" electric technology. This telltale indicator still exists for turn signals in 1999, to let the driver know if one of the turn signal bulbs has burned out the flash rate is different. Falge and Johnson also described some of the problems experienced by engineers in the early 1920s in developing signal lamps: reflector efficiency, painted reflectors, polished reflectors, prisms and pillows, uniformity of the pattern, spread of the pattern, dust and moisture in the assembly, and vent or drain holes. (Some things never change.)

In 1928, brake lamps were required to be approved in eleven states (Magdsick, 1928). Visibility of the signal at 100 ft (30 m), in normal sunlight, was required in six states. Three states specified a red color; two states specified red or yellow; and one state specified red, yellow, or green.

The first SAE work on signal lamps was all-inclusive, including everything on the rear of the vehicle except tail and license lamps. Signal lamps were defined as lamps indicating the driver's intention to diminish speed (deceleration lamp), to stop (stop lamp) or to change direction (turn signal lamp), by displaying a yellow light attracting attention in normal sunlight at a distance of 100 ft (30 m) to the rear and 45° to the left and 45° to the right of the vehicle (first geometric visibility requirement) (SAE, 1928). The minimum H-V luminance was specified to be at least 2 cd/in^2 (0.31 cd/cm^2) over the minimum illuminated area of 3.5 in^2 (22.6 cm^2). The reasons for a required minimum area were probably mainly practical. That was what was needed to make a good lamp. At all points within a 30° conical angle, the minimum luminance was specified to be at least 0.15 cd/in^2 (0.023 cd/cm^2) over the area of 3.5 in^2 (22.6 cm^2). The maximum intensity was specified as 25 cd in any direction. (Thus, these requirements included both luminance and intensity for the same lamp.)

The above SAE standard did not last long. In the 1930 SAE Handbook (SAE, 1930), it is indicated that the above standard was found unsatisfactory and had been canceled. Probably, it was found to be an unnecessary restriction.

At this time, IES and SAE were still jointly working on and publishing automotive lighting standards. IES (1930) and SAE (1933) contain revisions to the above SAE standard. First, red and yellow were allowed for rear signal lamps. The luminance requirement at H-V was 2 cd/in^2 (0.31 cd/cm^2), and the entire area of the lighting device was specified to be at least 3.5 in^2 (22.6 cm^2), with the minimum luminous area of the lamp of 2 in^2 (5 cm^2). In addition, the minimum intensity was 7 cd at H-V, and at all angles between 30° left to 30° right and 15° up, the minimum intensity was 0.5 cd.

In 1937, SAE established separate requirements for brake and turn signal lamps. (See Section 2.8. for the turn signal discussion and requirements after 1937.) The color for brake lamps (SAE, 1937) was red or yellow, but preferably red. The minimum area of the entire brake lamp was 3.5 in^2 (22.6 cm^2), with the minimum luminous area of 2 in^2 (12.9 cm^2). The photometric requirements called for a minimum of 7 cd at all points between 5° left to 5° right and 5° up. The minimum intensity from the entire signal lamp was 7 cd, and the minimum average luminance from any 2 in^2 (12.9 cm^2) of the luminous area of the lamp was 2 cd/in^2 (0.31 cd/cm^2). Finally, at all angles between 30° left to 30° right and 15° up, the minimum intensity was 0.5 cd.

Significant changes were made in the photometric requirements for brake lamps in 1953 (SAE, 1953). Red had an intensity requirement of 15 cd at the H-V test point, with no maximum specified. This was approximately the same as the photometric intensity requirements for the red and yellow rear turn signals for passenger (Class B) vehicles. (Class A mainly referred to trucks and heavy-duty vehicles, but Class A signals could be used on any vehicles.) Although yellow was still allowed for a brake lamp, this was not used by vehicle manufacturers. The distribution was over the same test point grid as today: 20° left to 20° right, and 10° down to 10° up.

The brake photometric intensity requirements were changed in 1955 (SAE, 1955). The red minimum intensity at H-V was now 30 cd. The ratio requirements still existed above the horizontal (at least three times the tail lamp intensity) and within 5° of H-V (at least five times the tail lamp intensity).

Breckenridge (1957), in the process of doing a pictorial review of signal lighting in connection with the celebration of the fiftieth anniversary of the founding of IES, to his surprise notes that although brake lights "have been in use for more than three decades, it is still common practice to depend upon a difference in intensity to distinguish them from tail lights."

The brake lamp photometric requirements in 1960 were changed to a minimum of 60 cd with a maximum of 300 cd at the H-V test point (SAE, 1961). Although both red and yellow were allowed, red was preferred, and all vehicle manufacturers used red.

Although in 1966 brake lamps were still not mandated in England, most new cars had brake lamps installed (Moore and Smith, 1966). In 1966, SAE revised the red photometric intensity requirements for brake lamps to 40 cd minimum and 300 cd maximum at H-V (SAE, 1967). In 1967, the requirements for multi-compartment lamps were created (SAE, 1968). Some of the requirements are shown in Table 6.

Table 6. Some of the 1967 SAE photometric requirements for multi-compartment brake lamps (cd).

Aspect	Number of compartments		
	1	2	3
H-V minimum	40	70	100
Maximum	180	240	300

The other test points in the pattern also were increased as the number of compartments increased. Even though multi-compartment requirements were created for tail lamps, brake lamps, and Class B (passenger vehicle) red rear turn signals, multi-compartment requirements were not yet established for yellow turn signals nor for Class A (mainly truck and heavy-duty vehicle) red signals.

The ECE Regulation 7 was adopted and enforced in 1967 for brake lamps (Cole et al. 1977). The photometric requirements for a single level brake lamp at H-V were 40 cd minimum and 100 cd maximum. Requirements were established for dual level (day/night) lamps, but these have not been used. The photometric grid extended from 20° left to 20° right, and from 10° down to 10° up. The geometric visibility requirement was 0.3 cd from 45° left to 45° right, and from 15° down to 15° up. There also was a ratio requirement of 5:1 in the area between 10° left to 10° right, and from 5° down to 5° up for the brake lamp when it was combined with the rear position lamp.

The original FMVSS 108 incorporated the SAE J586b, June 1966, for brake lamps. From this time on, the regulatory requirements for brake lamps in the U.S. were FMVSS 108 and not state and SAE standards. The photometric requirements initially incorporated into FMVSS 108 were the red brake values shown above (40 cd minimum to 180 cd maximum for one compartment). However, NHTSA stated that after January 1, 1973, the photometric requirements would be the (more demanding) red turn signal requirements for trucks and heavy vehicles, which for one compartment were 80 cd minimum and 300 cd maximum. These basic values have existed until the present (Office of the Federal Register, 1998).

It was not until 1970 that yellow was removed from the SAE standard as an allowed color for brake lamps, although red had been the common practice for many years (SAE, 1974). Red was the only color allowed by FMVSS 108 when it was created in 1968. Also at this time, the intensity values in the SAE standard were increased to match those required in FMVSS 108. The new SAE candela values are presented in Table 7.

Table 7. The 1970 SAE intensities for multicompartment brake lamps (cd).

Aspect	Number of compartments		
	1	2	3
H-V minimum	80	95	110
Maximum	300	360	420

FMVSS 108 in 1973 created the zonal photometric requirements (Office of the Federal Register, 1973). This meant the lamp did not have to meet each individual test point requirement if the sum of the test points in a zone met the zonal total photometric requirements. For a one-compartment brake lamp, as an example, the requirements in the 5° zone were those listed in Table 8. Later a note was added that the individual test points could be 60% of the individual test point requirement as long as the zonal total was met, but this note did not exist in 1973.

Table 8. Zonal photometric requirements (cd) in 1973 FMVSS 108 for a one-compartment brake lamp.

Test point location	Test point minimum intensity requirement	Zonal total minimum requirement
5U-V	70	380
H-5L	80	
H-V	80	
H-5R	80	
5D-V	70	

Lighting harmonization efforts between the U.S. and Europe started again in the late 1970s. (There had been previous harmonization activities in the 1920s and 1950s.) The minimum and maximum brake lamp requirements at that time were 40/100 cd in Europe (ECE) and 80/300 cd in the U.S. (NHTSA). After the harmonization efforts, the requirements were revised to be 60/185 cd in Europe and 80/300 in the U.S. This increased the overlapping window from 80-100 cd to 80-185 cd—sufficiently large to allow a lamp to meet both requirements. The GTB Harmonization Working Group activities continued through the 1980s and 1990s on different lighting subjects.

The SAE standard in 1984 (SAE J586, February 1984) included the following changes:

- Zonal requirements, incorporated by NHTSA in FMVSS 108, were added.
- Separate brake lamp standards were created for passenger cars and heavy-duty vehicles.
- Photometric design guidelines were separated from photometric requirements (analogous to ECE type approval and COP values). (This was never incorporated by NHTSA into FMVSS 108.)

The SAE standard for heavy-duty vehicles (SAE J1398, May 1985) was incorporated into FMVSS 108 in 1991 (Office of the Federal Register, 1991).

2.7. Center high mounted stop lamps

Some cars in the early 1970s in the U.S. had two supplemental high mounted brake/turn signal lamps mounted on the rear of the vehicle near the outboard edges. The photometric requirements (SAE J186a) for these lamps were as follows:

- red for supplemental brake or turn signal; 15 cd minimum at H-V to 60 cd maximum
- yellow for supplemental turn signal; 24 cd minimum at H-V to 120 cd maximum

Several studies were performed on high mounted stop lamps, both in the U.S. and Europe (see Section 3.3.7.). These studies led NHTSA to mandate the installation of a CHMSL on all passenger cars manufactured after September 1, 1985 (Office of the Federal Register, 1985). The photometric requirements for the red CHMSL (one lamp per vehicle) when it was introduced into FMVSS 108, were 25 cd minimum at H-V and 160 cd maximum. Transport Canada adopted almost the same requirement as NHTSA, except they only allowed a maximum of 130 cd. The NHTSA photometric requirements have not significantly changed from 1985 to 1999 (Office of the Federal Register, 1998).

Effective in 1993, NHTSA extended the requirement for the installation of a CHMSL to multipurpose passenger vehicles, large trucks, and buses (Office of the Federal Register, 1993).

On some trucks, the rear door has a structural member on the vehicle centerline, so two CHMSLs were allowed if they were located near the vehicle centerline.

Two high-level brake lamps were approved in Germany in 1980 and sold as add-on devices. Later they were made obsolete by the introduction of the factory-mounted CHMSL which was allowed in Europe after 1993 (Hella, 1999). In the early 1990s, European requirements for a high mounted stop lamp were added to ECE R7 (ECE R7, 1998). The photometric requirements were 25 cd minimum at H-V and 80 cd maximum.

2.8. Turn signal lamps

The first turn signals were developed in the early 1920s in the U.S. as aftermarket devices. Because the rear lamp at that time was normally only a single device, the turn signal was given by illuminated arrows. It was difficult to see these arrows in daylight, and efforts were made to improve them by using different colors (Hitzemeyer et al., 1977). However, the arrow idea only lasted in production for a few years.

Falge and Johnson (1923) indicate that green, yellow, or red arrows were initially used before any standards existed. These arrows were steady burning until canceled manually by the driver. An example of this type of turn signal is shown in Figure 6. Much later, self-canceling and flashing turn signals came into existence.

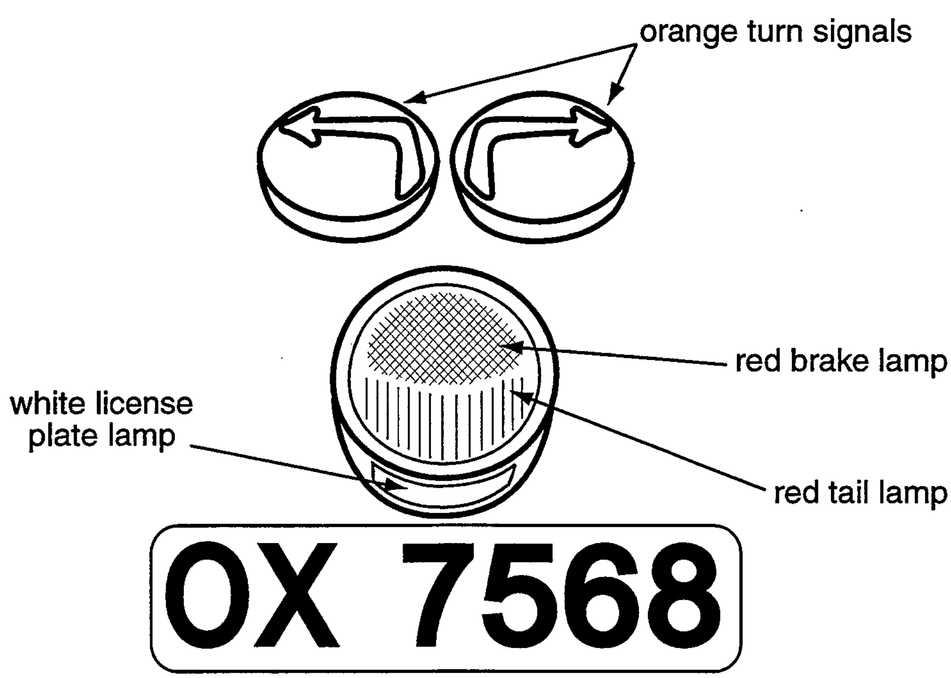

Figure 6. A schematic representation of a 1926 Rolls-Royce with yellow turn signal arrows, and brake, tail, and license plate lamp in the assembly (Henry Ford Museum, Dearborn, Michigan).

Much of the discussion for the early turn signals is covered in the brake lamp section above because there was only one standard to cover everything. In 1937, SAE finally established separate requirements for brake lamps and turn signal lamps (SAE, 1937). However, there was not any provision for turn signals on the front of the vehicle. One noticeable change in 1937 was that red and yellow were allowed for the rear turn signal, but if the brake lamp and the turn signal lamp were separate, then red was for brake and yellow was for the turn signal. Prior to this, all turn signal lamps had been specified as steady burning (not flashing). Now the SAE acknowledged that flashing greatly increased the conspicuity of the turn signal. Therefore flashing was proposed (60 to 150 flashes per minute) with the on period at least 1/3 of the flashing cycle. All of the area and photometric requirements were the same as those mentioned in Section 2.6 for brake lamps in 1937. The minimum area of the entire brake lamp was 3.5 in^2 (22.6 cm^2) and the minimum luminous area was 2 in^2 (12.9 cm^2). The photometric requirements included a minimum of 7 cd at all points between 5° left to 5° right and 5° up, and the minimum average brightness of 2 cd/in^2 (0.31 cd/cm^2) from any 2 in^2 (12.9 cm^2) of the luminous area of the lamp. Also, at all angles between 30° left and 30° right and 15° up, the minimum intensity was 0.5 cd. Note that in 1937 there was no difference in the required intensity if the color for the turn signal was red or yellow. Finally, the SAE standard introduced the requirement for a telltale (turn signal indicator) to give a clear and unmistakable indication to the driver that the turn signal was flashing, if the turn signal was not readily visible to the operator of the vehicle.

In the 1930s, turn signals were developed as standard equipment in Europe, probably influenced by the large number of bicycles. The European turn signals were of the semaphore type (with or without motion). They were illuminated from inside with an intensity of about 1 cd. These semaphore turn indicators dominated the European scene into the 1950s. The first U.S. flashing turn signals were introduced in 1939 (General Motors, 1965). These turn signals were flashing red lamps in the rear and flashing white lamps in the front.

The first SAE recognition of front turn signals is in SAE (1939). Front turn signals were proposed as white or yellow, and this lasted for many years. The rear turn signals were still allowed to be red or yellow. Some rear turn signals continued to be steady burning pointed arrows rather than a flashing turn signal lamp. The standard listed different visibility distance requirements, based on the implementation of the signal. For example, if a signal was not located on each side or was not flashing, the required visibility distance was 100 ft (30 m); no visibility distance was required if a signal was on each side and was flashing.

In 1949, SAE began to make some modern day technical revisions to the signal lamp standards (SAE, 1949). Class A and Class B turn signal requirements were established. The idea was to step up the requirements gradually starting with the signal lamps for trucks and heavy-duty vehicles. For these vehicles, Class A was required. Class B was, for the moment, enough for passenger cars. Gradually and voluntarily, most manufacturers of passenger cars started using Class A. Class B maintained the existing minimal photometric values of previous years. The new Class A minimum requirements were 100 cd for red rear lamps and 400 cd for yellow or white front lamps.

Significant changes were made in the photometric requirements for turn signal lamps in 1953 (SAE, 1953). Class A turn signals, which could be used on any vehicle, were divided into two types. Type I indicated a change in direction by giving flashing signals on the side toward which the turn would be made. Class A, type I had an area requirement of at least 12 in^2 (77.4 cm^2). Type II indicated a change in direction by flashing arrowheads on the side toward which the turn would be made. This type II turn signal was a carry over from previous standards in which the requirement was visibility of the turn signal at some distance. The type II turn signal was not required to meet the photometric requirements of the type I signal. Class B turn signals had an area requirement of at least 3.5 in^2 (22.6 cm^2) and had lower photometric intensity requirements than Class A, and could be used on passenger cars and on other smaller vehicles. No maximums were specified. Red and yellow were allowed on the rear. White and yellow were allowed on the front. The period in the 1950s and early 1960s was a transition period. Turn signal requirements previously included visibility at some distance. Now turn signal photometric intensity requirements were being phased in.

The changes in the SAE requirements from 1953 to 1967 are illustrated in Table 9. Starting in 1953, the test point angles were the same as today: 20° left to 20° right, and 10° down to 10° up.

Table 9. Illustration of how the Class A and Class B SAE photometric minimum and maximum requirements (cd) for turn signals changed from 1953 to 1967.

Class A, type I	1953	1956	1957	1960	1966	1967
Red	100/-	100/-	100/-	100/300	80/300	80/300
Yellow	300/-	300/-	250/-	200/-	200/900	200/900
White	600/-	600/-	400/-	400/-	300/-	-
Class B	1953	1956	1957	1960	1966	1967
Red	15/-	30/-	30/-	60/300	60/300	40/300
Yellow	50/-	90/-	75/-	180/-	180/-	120/900
White	100/-	180/-	120/-	300/-	300/-	-

Starting with 1956, ratios existed between the tail lamp and the red rear turn signal. In addition, a new requirement was established that the red rear turn signal should override the brake lamp on the side with the flashing turn signal, if these two lamps were optically combined.

Most cars in England in 1954 used the semaphore arm as the turn signal indicator (Moore and Smith, 1966). By 1965, the flashing turn signal was used almost universally.

Interestingly, the change of the turn signal colors from white (front) and red (rear) to yellow was first taken up in the U.S. in the late 1950s by the members of the Vehicle Lighting Committee of the Automobile Manufacturers Association (AMA). They convinced the GTB about the advantages of yellow turn signals at a meeting in 1960. GTB in turn convinced the Europeans, and the ECE in 1967 required yellow turn signals in the rear and yellow or white turn signals in the front. The U.S., on the other hand, decided to require yellow turn signals in the front and red or yellow in the rear. The original reasons were that yellow in the front separated the turn signals from reflections in the chrome, and yellow signals in the rear were not shown to be cost effective (Maurer, 1980).

Under UN organization, several ECE regulations were prepared and adopted. The ECE Regulation 6 for turn signal lamps was approved and put into practice in 1967 (Cole et al. 1977). The photometric requirements for a yellow rear turn signal in 1967 were for a single level 60 to 200 cd, and for a double level 175 to 700 cd during the day and 40 to 120 cd during the night.

The photometric grid extended from 20° left to 20° right, and from 10° down to 10° up. Geometric visibility requirements were established over the same field of view as other rear lamps. The photometric grid was approximately the same as in the U.S., but the intensity values were different.

In 1968, NHTSA was formed in the U.S. Department of Transportation. NHTSA established the FMVSS 108 for lighting. FMVSS 108 incorporated the SAE J588d, June 1966, for turn signal lamps. From this time on, the regulatory requirements for turn signal lamps in the U.S. were FMVSS 108 and not state regulations and SAE standards. The photometric requirements incorporated by NHTSA into FMVSS 108 were the 1967 SAE Class A intensity values mentioned in Table 9.

In 1970, multicompartment requirements were created for turn signal lamps (SAE, 1974); see Table 10. The numerical values for Class B turn signal lamps were finally removed. These had not been used by any manufacturers for several years prior to 1970.

Table 10. 1970 SAE requirements (cd) for multicompartment turn signals.

Color	Number of compartments		
	1	2	3
Red	80/300	95/360	110/420
Yellow	200/750	240/900	275/1050

FMVSS 108 in 1973 created the zonal photometric requirements (Office of the Federal Register, 1973). This meant the lamp did not have to meet each individual test point requirement if the sum of the test points in a zone met the zonal total photometric requirements. For a one-compartment red turn signal, the zonal values were the same as for a one-compartment red brake lamp. As an example, Table 11 lists the requirements in the 5° zone for a one-compartment yellow turn signal lamp. Later a note was added that the individual test points could be 60% of the individual test point requirement as long as the zonal total was met.

Table 11. Zonal requirements (cd) in the 1973 FMVSS for a one-compartment yellow turn signal.

Test point location	Test point minimum intensity requirement	Zonal total minimum requirement
5U-V	175	950
H-5L	200	
H-V	200	
H-5R	200	
5D-V	175	

SAE J588f, November 1978, made a revision for yellow rear turn signals, which was incorporated into FMVSS 108 in 1985 (Office of the Federal Register, 1985). The immediately previous red and yellow signals had a ratio of red to yellow of 2.5. Now that ratio was changed to 1.6. This was achieved by reducing the requirements for the rear yellow turn signal. No change was made in the requirements for the front yellow turn signals. First, this reduced many complaints from drivers that felt the rear yellow turn signals in the U.S. were too bright (glaring), and second, this harmonized closer with ECE rear turn signal lamps to create a "window of opportunity." The changes for the compartments for yellow rear turn signals are listed in Table 12. The zonal requirements in the 5° zone for a one-compartment yellow rear turn signal lamp are shown in Table 13.

Table 12. Photometric requirements (cd) for yellow rear turn multicompartment signals in the 1978 FMVSS.

Aspect	Number of compartments		
	1	2	3
H-V minimum	130	150	175
Maximum	750	900	1050

Table 13. Zonal requirements (cd) for a one-compartment yellow rear turn signal in the 1978 FMVSS.

Test point location	Test point minimum intensity requirement	Zonal total minimum requirement
5U-V	110	610
H-5L	130	
H-V	130	
H-5R	130	
5D-V	110	

Turn signals were harmonized in the same way as brake lamps. When the U.S. reduced the yellow intensities because of the red to yellow ratio and Europe increased the maximum intensity allowed for yellow rear turn signals and red brake lamps, there became a "window of opportunity" for lighting harmonization. The minimum and maximum turn signal requirements at that time were 50/200 cd in Europe (ECE) and 200/900 cd in the U.S. (NHTSA). After the harmonization efforts, the requirements were revised to be 50/350 cd in Europe and 130/750 in the U.S. This created a previously nonexistent overlapping 130/350 cd window—sufficiently large to make a lamp meet both requirements.

In 1984, separate turn signal standards were created for passenger cars and heavy-duty vehicles (SAE J588, November 1984, and SAE J1395, April 1985). While passenger cars still had multicompartment requirements, for heavy-duty vehicles there were only photometric requirements for one-compartment lamps. This change for heavy-duty vehicles was incorporated into FMVSS 108 in 1991 (Office of the Federal Register, 1991).

The ECE R6 in 1999 (ECE, 1998) is only slightly changed from the regulation adopted in 1967. The only photometric change is that the maximum allowed intensity is now 350 cd. (See paragraphs above for original values and harmonization changes to increase the maximum.) The geometric visibility field of view was increased to 80° outboard instead of 45° outboard.

2.9. Rear fog lamps

The first rear fog lamp was introduced in Germany in 1966 (Hella, 1999). ECE approval for European-wide use of rear fog lamps did not occur until 1978 when ECE R38 was issued. R38 specified a minimum intensity of 150 cd between 10° left to 10° right and 5° down to 5° up, and a maximum of 300 cd in any direction. The apparent surface was limited to a maximum of 140 cm^2. These requirements have existed in R38 until the present (ECE R38, 1996).

There has not been any significant usage of rear fog lamps in the U.S. An SAE standard was not created until 1987 (SAE J1319, August 1987). The SAE J1319 photometric requirements for a rear fog lamp were the same as for a one-compartment brake lamp (80 cd minimum and 300 cd maximum), with the same test point grid (20° left to 20° right, and from 10° down to 10° up). There has not been any change in the SAE requirements for rear fog lamps since 1987.

In Europe, it is allowed to have one rear fog lamp mounted on the rear on the driver side of the vehicle, or two rear fog lamps mounted symmetrically about the vehicle centerline. In the U.S., it is allowed to have one rear fog lamp mounted on or to the left of the vehicle centerline, or two rear fog lamps mounted symmetrically about the vehicle centerline. There is a 100 mm spacing requirement for the distance between the rear fog lamp and the brake lamp in Europe and the U.S.

Rear fog lamps became mandatory in Europe in 1991 (ECE R48; 1998). Rear fog lamps are not required in the U.S. and are not included in FMVSS 108. They are controlled by SAE standards and state regulations.

2.10. Back up (reversing) lamps

Back up lamps were used in some installations before any standard was developed. Figure 7 shows such an integrated back up lamp from 1927. The first SAE standard for back up lamps was adopted in 1947 (SAE, 1948). This first standard had a downward oriented beam pattern that was to provide rearward illumination for the driver. At this time, the purpose of a back up lamp did not include alerting a pedestrian to motion of the vehicle. The first photometric requirements included a maximum of 800 cd between the horizontal and 1.5° down, and a maximum of 300 cd at and above the horizontal.

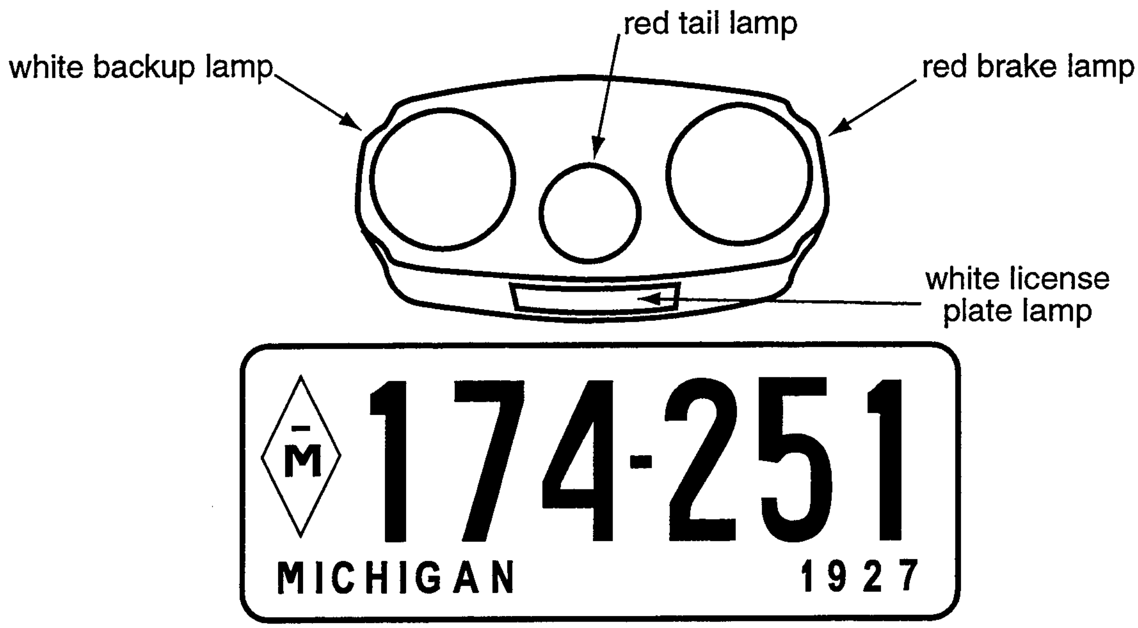

Figure 7. A schematic representation of a 1927 Chrysler multifunction rear lamp: back up, tail, brake, and license plate lamps (Henry Ford Museum, Dearborn, Michigan).

By the time back up lamps were incorporated into FMVSS 108 in 1968, the photometric requirements were considerably different. The maximum was still 300 cd at H and above (SAE, 1970). The minimum at H-V was 80 cd. The test point grid ranged from 45° left to 45° right and from 10° up to 5° down. One or two back up lamps were allowed on a vehicle. However, if only one back up lamp was installed on the vehicle, it had to meet twice the candlepower requirements. It was also allowed to have two unsymmetrical back up lamps. This meant that each back up lamp could be tested individually and the values added to determine whether the combined units met twice the candlepower requirements. These same photometric requirements still exist in FMVSS 108 in 1999.

The ECE R23 for reversing lamps was created and enforced in 1971 (Cole et al. 1977). The photometric requirements were 80 cd minimum at H-V, and 300 cd maximum above the horizontal line. There was a maximum of 600 cd below the horizontal line. The test point grid extended from 45° left to 45° right and from 10° up to 5° down.

The ECE R23 photometric requirements in 1999 (ECE R23, 1996) are very similar to those adopted in 1971. However, now for an installation where two reversing lamps are on the vehicle, the inboard photometric angle need only be tested to 30° with a minimum of 25 cd.

2.11. Harmonization

Lighting regulations proceeded pretty much independently in the U.S. and Europe. The regulations for many years, although somewhat similar, did not allow, in most cases, a "window of opportunity." When serious harmonization efforts occurred, then some successes were achieved. Back up lamps and tail lamps are essentially harmonized. License plate lamps, when adjusted to take into account the different plate sizes, are close to harmonization. Rear fog lamps and CHMSLs are close to harmonization, when they are properly mounted.

For many years, brake and turn signal lamps were difficult to harmonize. When the maximums and minimums were changed in the U.S. and Europe in the late 1970s then a "window of opportunity" was created for brake and turn signal lamps. Another success in harmonization activities occurred in the middle 1990s. The GTB Harmonization Working Group had been working on the subject of geometric visibility for signal lamps. Proposals were made by the Working Group to GTB and then to GRE for revisions to existing ECE regulations. In addition, GTB submitted a petition to NHTSA to revise FMVSS 108. These geometric visibility recommendations would allow either the European photometric method of a specified candela value requirement over a stated angular field or the U.S. area method over an angular field. These two methods would be considered acceptable in both FMVSS 108 (U.S.) and the ECE regulations (Europe). The ECE regulation changes have been accepted by GRE and WP29, and NHTSA has issued a NPRM (notice of proposed rulemaking) to make the changes in FMVSS 108. When these geometric visibility changes are final in both the U.S. and ECE regulations, it will increase the harmonization of rear signal lighting.

3. Do Current Rear Signals Fulfil Their Tasks?

When we evaluate the extent to which the present rear lighting systems fulfil their purposes we must base this on available empirical evidence. There is a vast literature relevant to rear lighting and rear end collisions. Although only a limited number of these studies are discussed in Sections 3 and 4, we think they are consistent with general trends and results reported in other studies.

When it comes to the evaluation of rear signal lamp design, a basic issue is the choice of evaluation criteria. Roszbach (1972) analyzed this problem and concluded that none of the three most common evaluation approaches (accident studies, indirect field studies, and indirect laboratory studies) are fully satisfactory. They suffer from low reliability, low validity, or both. Furthermore, they all are based on an analysis of the problem that determines which alternatives to test. Instead of recommendations for specific configurations, he proposes guidelines and restrictions. A problem associated with proposed new designs that has not received enough attention is the confusion that may be produced during the transition period when vehicles are equipped with both old and new designs. Often positive and negative effects, and long-term and short-term effects, must be weighed against each other.

3.1. Accident statistics of rear end crashes

Moore (1952) noted that the risk of a rear end collision in Britain was four times greater at night than during daytime. He suggested that the rear lamps then in use were often inadequate. In another study, he compared the risk of a rear end collision for cars before and after the war. After the war, vehicles had more intense rear lights. The results showed that, for every postwar car hit during the day, 0.4 were hit at night; and for every prewar car hit in the day, 2.3 were hit at night. Thus, rear lamp intensity is obviously an important safety factor at night.

In 1972, the strict British legislation for nighttime parking of vehicles was eased. Certain classes of vehicles were allowed to park at night under certain circumstances (e.g., speed limit 48 km/h or less) without showing previously compulsory parking lights. Johnson (1974) studied the effect of this regulatory change on collisions with vehicles parked at night (presumably mainly rear end crashes). His conclusion from this analysis was that the reduction in vehicle markings at night resulted in a 36 % increase of parked vehicle involvement in nighttime crashes. These results illustrate the importance of rear vehicle marking at night.

Mortimer (1989) noticed that while most rear end crashes are approximately equally distributed over the day and night, this is not the case for parked vehicles. The number of parked cars hit from the rear at night is twice the number of parked cars hit during the day.

Mortimer and Post (1972) divided the crashes according to the action taken by the struck car. Their conclusion was that the differences in proportion between day and night crashes were small. However, on limited-access roads, a majority of the crashes occurred on straight stretches without slowing, while on non-limited-access roads a majority of the crashes occurred when the lead car was braking or stopping.

As already mentioned, rear end crashes constitute a high proportion and a steadily increasing part of all crashes. It has been noted (Mortimer, 1979) that in over 50% of rear end crashes that did not involve parked vehicles, the struck vehicle was stationary. Almost 30% of the hit vehicles were moving very slowly (< 32 km/h). In another study, Mortimer (1981) reported that from the analysis of a study of CHMSLs, it could be inferred that 50-80% of the struck vehicles were either stopped or moving very slowly. In a more recent study, Knipling et al. (1992) reported that an even larger proportion of the vehicles hit from the rear (about 70%) were stopped at the moment of collision and had been stopped for 2-6 s. (However, it is not clear how this time of 2-6 s was obtained). A critical question is whether a large proportion of stopped vehicles consists of cars that stopped after the rear driver began interacting with them, or if they were stopped during the entire interaction.

Rear end crashes are one of the most frequent crash types. For example, in the U.S. there are currently about 1.9 million rear end accidents every year (NHTSA, 1998), and they are responsible for about 21% of the total crash costs (Wang et al., 1996). (The real figure may be even larger as argued below.)

According to U.S. national accident statistics (NHTSA, 1998) the rear end accidents constitute 28% of all motor-vehicle collisions (5% of the fatal collisions, 29% of the injury collisions, and about 28% of the property damage collisions). The fatality rate per 1,000 crashes is lower for rear end crashes than for any other vehicle collision type. Rear end collisions are the third most serious collision after head on and angular collisions in terms of injury rate per 1,000 crashes. From these figures, it looks as if rear end collisions, even if they are frequent, are usually less serious than both frontal and angular collisions.

Rear end crashes often cause injuries that are very difficult to diagnose at the scene of the crash. Often there is no visible injury or trauma. Recent Swedish experience (Krafft et al., 1997) indicates that a large proportion of road crash victims treated at hospitals are treated for injuries received in rear end collisions. As many as 50% of all permanent impairments in road traffic crashes are related to neck injuries, half of which are sustained in rear end crashes.

Many neck injuries are not detected at the crash site because of the lack of evident injury. The neck injuries are often not discovered until weeks, months, or even years after the collision, with a delayed onset of neck and head pain. Neck injuries from rear end collisions are a substantial hidden problem. They may result in lifelong impairment despite being formally classified as "no injury."

There are generally three types of rear end crashes: First, one in which the rear driver is interacting with the lead car in normal driving; second, one in which the rear driver is driving independently until he or she tries to avoid a crash; and third, one in which the hit vehicle is parked. According to Perchonok (1972) over half of the rear end crashes in rural areas and about two-thirds of the rear end crashes in the urban areas happen in situations which are not really car-following situations.

Rear end collisions are the primary collision type influenced by rear signaling efficiency. However, it should be noted that the rear signaling system could also influence other less common types of collisions, although to a lesser extent (e.g., collisions in connection with lane changes, merging, left and right turns in intersections, U-turns, and backing).

3.2. General problems with present rear signal lamps

In this section a number of problems with present rear signal lamps are discussed. The studies referred to are examples of the research in the area—not a complete bibliography. Several good general studies and reviews of rear lighting are available, for example Finch and Horning (1968); Nickerson et al. (1968); Rockwell and Banasik (1968); Rockwell and Safford (1968); Projector et al. (1969); Mortimer (1970); Cole et al. (1977); Sivak (1978); Henderson et al. (1983); Mortimer (1986); and Sivak and Flannagan (1993).

Forbes (1966) noted a difference between physical photometric measurement and perceptual measurement dimensions. The relation is logarithmic. This is a basic psychophysical finding, well known from human factors research. Forbes presents curves and equations for the relations between a number of physical and perceived aspects.

Early rear lights were generally not bright enough. Studies of tail light intensity in Britain yielded the following results. Moore (1952), referencing the 1947 SAE standard of tail lamps (0.25 cd), measured a sample of the British car population and found that 75% of tail lamps failed to meet the U.S. requirement. (Note that each car had only one tail lamp.) Next, he determined whether such a "high" requirement as 0.25 cd was excessive. His results showed that the figure was rather too low, but realistic. He reported that an intensity of 0.25 cd could be detected at a distance of 122 m at night. (Up to about 1950, the intensities of tail lamps were usually less.) He also noted that the brighter the light is, the closer it is perceived to be. Although greater intensities are commonly used today, rear light intensity may still be a problem in special situations (e.g., fog).

Originally, SAE made no intensity distinctions for signal lamp function of different colors (i.e., red or yellow on the rear; white or yellow on the front). Kilgour (1960) explains some of the changes made from the early SAE standards. Tests in normal sunlight conditions of Michigan and bright sunlight conditions of Arizona determined the intensity ratios for equal effectiveness of red, yellow, and white. The candela intensity ratios for these colors were determined to be 1:3:5.

Some researchers believe that signal lighting luminances are at least as important as signal light intensities (e.g., Cole et al., 1977, Schmidt-Clausen, 1985). Consequently, they argue that luminance should be part of the regulations. Cole et al., for instance, proposed regulations specifying minimum and maximum intensities, maximum luminances (e.g., 1,000 cd/m^2 for tail lamps and 30,000 cd/m^2 for brake lamps), and minimum and maximum areas. However, the majority of the experts seem to share the opinion that signal light intensity is dominant and that signal light luminance, although of some importance, is secondary.

Flannagan et al. (1998) have explicitly studied this question. The concept of multicompartment lamps is based on traditional lamp construction with a filament bulb in each compartment. When the lamp area is increased by increasing the number of compartments, one way not to lower luminance too much is to prescribe higher intensities for multicompartment lamps. However, with new light sources (e.g., LED), the situation changes. Can the luminance or area controls in the requirements now be completely eliminated, regulating lamps only in terms of intensity? Flannagan et al. found that luminance has some influence and suggest that a standard area of 225 cm^2 be chosen as the basis for an area-dependent intensity requirement, in which intensity values increased with area in the multiple of 225 cm^2.

In the following paragraphs, the performance of rear lighting is examined in a general way. Some negative aspects of the rear lighting functions are pointed out and commented on.

Rear lights have the same intensities during day and night, in good weather and bad (a compromise intensity). The ECE Regulations 6 and 7 in fact allow one intensity or two intensities (day and night) for brake and turn signals. Since ECE also has a rear fog lamp regulation 38, all three functions have some provision for different intensities depending on ambient conditions. However, as far as we know, no car manufacturer is using the two-level alternative for brake and turn signals.

Several researchers and organizations have proposed intensities for two or even three-level rear lighting systems. Because the various rear lighting functions interact in a complicated way, such proposals have to consider at least all of the three main functions (tail, brake, and turn). Several such proposals are presented in Table 14.

Table 14
Proposed photometric values for multilevel lamps (minimum/maximum, all values in cd).

	Night	Day	Fog (day and night)
Tail lamps			
ECE R7 (1998)*	4/12	--	150/300
AMA (1967)	3/12	--	
Bol and Decker (1977)	8/18	--	30/240
Mortimer (1977)	4/15	--	
Brake lamps			
ECE R7 (1998)	30/80	130/520	
AMA (1967)	50/150	250/750	
Bol and Decker (1977)	80/185	300/2400	300/2400
Mortimer (1977)	80/190	300/-	
Fowkes & Storey (1993)	32	66	66
Turn Signals			
ECE R6 (1998)	40/120	175/700	
AMA (1967)	60/180	300/900	
Bol and Decker (1977)	100/235	400/5800	460/5800
Mortimer (1977)	80/320	425/-	
Lucas (RRL, 1963)	100	500	

*The values for fog are from ECE R38 (1996) for rear fog lamps. Rear fog lamps are meant to provide the marking function of tail lamps in fog.

Pasta and Soardo (1979) suggested that low placement of a brake lamp with a vertical-gradient light distribution produces good visibility at long distances even in daylight without the problem of glare at short distances at night. They propose a specific light distribution and suggest that two intensity levels are not necessary.

Rear light functions rely on an intensity difference that is often perceptually difficult to detect. Researchers do not agree what constitutes an adequate intensity difference. For instance, Rockwell and Safford (1966) found that when the ratio of brake light to tail light intensity increased to 5.3:1, both reaction time and confusion risk were reduced. Above this ratio, little added benefit was noted. Forbes (1966), however, received positive effects of ratios even up to 22.

Fisher and Cole (1974), studying intensity of traffic signals, found that red signals need not be as bright as green and yellow signals. They recommended that the intensity ratios should be 1.33 for green to red signals, and 3 for yellow to red signals.

Rear light functions might not be sufficiently separated in space. However, the suggested remedies differ. For example, Case et al. (1969) studied the effects of physical separation of function (in space) and redundancy of mode—that is, more than one mode (e.g., intensity and pattern). They found that redundancy of mode resulted in a 30% improvement of correct responses. Physical separation resulted in a 75% improvement of correct responses. On the other hand, there was no effect of the specific pattern used as long as the two principles were followed.

Mortimer (1969) studied the distance at which a separation between two red lights could be detected. He found that lamp area was not a significant variable. The results show that the larger the separation, the better the performance. He compared separations of 102, 152 and 204 mm in nighttime situations. A separation of 152 mm was detected at a distance of 122 m. At a distance of 300 m, none of the separations were visible.

Helliar-Symons and Irving (1981) investigated how rear fog lamps influenced the visibility of brake lamps in fog. They found that even a fairly small separation distance of 50 mm between the fog and brake lamps improved the visibility of the brake lamps considerably. Akerboom et al. (1993) reported that rear fog lamps introduced an ambiguity that led to false alarms and slow reaction to brake lamps. A CHMSL reduced, but did not eliminate, these disadvantages. Fowkes and Storey (1993) studied the effect of separation distance between tail lamps and brake lamps. They proposed a minimum separation distance of 100 mm. They argued that with such a separation, rear fog lamps, together with the tail lamps, do not seriously mask the brake signal.

Differences in color between the rear light functions might not be large enough. The color of rear lights is a recurring theme. Opinions differ on the use of colors. In the 1920s and 1930s, different colors (green, yellow, and red) were evaluated for use as signal lamps. After various rounds, the choice of red dominated, save for the occasional use of yellow for rear turn signals.

Rear lights are often seen in the visual periphery. Consequently, peripheral discrimination of colors is relevant. In the periphery, color recognition declines (Lythgoe, 1931; Hunt, 1952; Moreland and Cruz, 1959). Thus, color recognition is not a good basis for discrimination even for persons with normal color vision. Sivak et al. (1999) found that color differences are insufficient to discriminate between signals outside of center vision. They suggest that other coding parameters, such as intensity difference or steady versus flashing signal, are more salient.

On the other hand, Mortimer (1970, 1977) suggested that a total color separation of functions should be applied to all three major rear signal lamps. Tail or presence lamps should be greenish-blue, turn signal lamps yellow, and brake lamps red. Nickerson et al. (1968) shared the same opinion as Mortimer. Many U.S. passenger cars only have red rear signal lamps; European vehicles must have yellow turn signals.

Rockwell and Safford (1968) made comparison tests between red and yellow tail lamps with red brake lamps. The results indicate that a yellow tail lamp with a red brake lamp of equal intensity is equivalent to a red tail lamp with a red brake lamp, with an intensity ratio of 1:5.

Safford et al. (1970) found that red is perceived to be further away than its objective position, and blue is perceived to be closer. They suggested exploiting this difference by using different colors in the rear signaling system. The effect, however, is comparatively small. Its use must be weighed against the fact that the colors of the present system are well established.

Chandra et al. (1992) studied the effects of making brake lamps appear in the off state the same color as the car body. They distinguished the effect of luminance contrast from chromaticity contrast. Their results suggested that there is a small but significant increase in the effectiveness of body colored brake lamps that provide chromaticity contrast as well.

For persons with defective color vision, such as so-called red-blind persons (protanopes) and green-blind persons (deuteranopes), color cues are problematic. It is well known that in artificial situations, where color is the only clue, color defective persons are error prone. However, in real traffic situations, where there are redundant cues (e.g., lamp position), color defective persons make few mistakes. Shirley et al. (1966) investigated the effect of color defective vision on identification of flashing signals corresponding to turn signals. The colors used were red, yellow, green, blue, and white. Their results show that color defective persons make more mistakes at lower levels of signal intensity. They also make more mistakes in daylight compared to night (yellow is confused with red, and white is confused with green). The most confused color is yellow followed by white, green, red, and blue. From this specific point of view, blue is the preferred signal color!

Taylor and Ng (1981) studied accident data from insurance claim files to determine the relative effectiveness of red and yellow rear turn signals. The background was that Europe and UN ECE require yellow rear turn signals, while the U.S. and Canada allow both yellow and red. They found no significant differences in rear end collisions, and consequently recommended no change to the U.S. and Canadian regulations.

Rear lights frequently might produce an ambiguous outline of the vehicle at night. Two red points could be a car, a truck, two motorcycles, or two cars partially obstructing each other. Fisher and Hall (1978) investigated the effect of tail lights on the estimation of change of vehicle headway. They found that when the rear surfaces of a vehicle are visible, as they are in daylight and in most street lighting situations, tail lights have no influence on the estimation of headway.

Rear lights have a relatively short life time, and little redundancy. For instance, the failure of one lamp may cause a false signal. Mortimer et al. (1974) surveyed the malfunctions of rear lamps and conducted studies in a simulator to estimate the effects of such malfunctions. Their conclusions were that about 4% of vehicles with single-compartment lamps had failure of a tail, brake, or turn signal lamp on one side. This was less common on vehicles with multi-compartment lamps. The results show that lamp failures lead to interpretation errors and elevated reaction times. Furthermore, they found that many drivers did not use their turn signals. Huhn et al. (1997) suggested using a redundancy pattern so that when one lamp fails, one of the other lamps automatically substitutes.

Rear lights are exposed to heavy degradation. Rosig (1970) reported a survey conducted in Germany between 1966 and 1969. In it, about 2.5% of the vehicles inspected had some lighting deficiency. The report, however, did not distinguish between deficiencies in headlamps and rear signal lamps. Cole et al. (1977) showed that signal malfunctioning in Australia is 5.7% for tail lamps and 11.3% for brake lamps. However, there was no difference in malfunction rate between areas with and without annual vehicle inspection.

A U.S. survey of the operation of rear lamps between 1979 and 1984 (Olson, 1985), determined that about 2% of signal lamps were not working. Note that Rosig, as well as Cole and Olson et al. merely checked whether the lamps were working, not how *well* they worked (e.g., photometric values were not measured).

Schmidt-Clausen (1985) performed static and dynamic tests to rate the luminances of brake lamps and rear position lamps. He observed new lamps and also measured the intensity values of rear lamps on cars in use. His results show that the older the car, the lower the intensity of the rear lamps. The intensities of rear lamps in use were, on the average, half of the values required by the regulations. Many of the rear lamps on cars older than five years did not meet the minimum values prescribed in the appropriate ECE regulation (tail lamps: ≥4 cd; brake lamps: ≥40 cd, turn signals: ≥50 cd).

Cobb (1990) performed roadside surveys of vehicle lighting in Britain in 1989, including rear signal lamps. He determined whether the lights worked, and recorded their intensities. He found that a large proportion of the vehicles in traffic did not achieve the intensity values required in the applicable ECE regulations. The worst situation was observed for rear fog lamps on heavy vehicles. For passenger cars, the situation was as follows:

- 16% of rear position lamps did not reach the minimum required intensity of 4 cd
- 24% of rear turn signals did not reach the minimum required intensity of 50 cd
- 46% of brake lamps did not reach the minimum required intensity of 40 cd
- 54% of rear fog lamps did not reach the minimum required intensity of 150 cd

The main causes of the low values were dirt, cracked lenses, poor reflector condition, condensation, and blown bulbs. There is no reason to think that the situation in Britain is any different than the rest of Europe. No corresponding surveys appear to have been conducted in the U.S.

Sivak et al. (1997) studied the effects of realistic levels of dirt on the light output of rear lamps. A route of almost 500 km was driven in three conditions (dry, wet, and snowy/salty), equivalent to approximately ten days of normal driving for a typical U.S. driver. The results show a decrease in light output throughout the beam pattern. Driver-side lamps collected slightly more dirt than the passenger side. In dry conditions, the reductions were all lower than 8%; in wet and snowy/salty conditions some values were reduced by more than 25%. Greatest reductions occurred in the central area of the light distribution (near the optical axis).

Rockwell and Safford (1968) studied the intensity ratio of brake lamps to tail lamps of cars in traffic in Ohio. They found that about 15% of the cars tested had ratios below the legal minimum 5:1. This leads to significantly reduced response times. The proportion of cars having this defect increased with the age of the car.

Regulatory requirements on rear lamps are not internationally harmonized (see Section 2.11). This adds cost for producers and consumers and likely adds to road user confusion in international traffic.

When drivers have a choice, they often do not use signal lamps properly. Drivers often fail to use turn signals and rear fog lamps, and when used, they often forget to turn them off.

3.3. Special problems with specific rear signal functions

In the following paragraphs the performance of rear lighting systems is evaluated using the list of rear lighting functions presented in Section 1.3.2.

3.3.1. Vehicle presence (conspicuity)

There is little difficulty detecting vehicle presence except in reduced visibility conditions (such as fog, heavy snow, smoke, or dust). Finch and Horning (1968) and Mortimer (1977) addressed the issue of the optimal color for rear fog lamps. They concluded that in day fog, red is most visible, while in night fog, greenish-blue and red are most visible. The degree of fog penetration is determined primarily by intensity. Rear fog lamps should have a considerably higher intensity because lamp visibility is exponentially related to lamp intensity. Finch and Horning (1968) suggested that rear fog lamps should be at least 100 times more intense than normal rear lamps (about 500 cd). Moore and Smith (1966) found improvements in fog visibility increased with substantially increased lamp intensity. For example, visibility from 30 m at 2 cd, to 73 m at 5000 cd.

Lythgoe's (1973) research suggested that visibility of rear lights in fog is determined not only by intensity, but also by area. However, he apparently did not vary intensity and area independently, making interpretation unclear.

Lancashire (1978) analyzed rear end crashes in Australia, and the use of rear fog lamps as a countermeasure. His analyses showed that rear end crashes in fog are rare and that rear fog lamps are expensive. He suggested that rear fog lamps are not cost effective, and consequently should not be compulsory.

3.3.2. Indication of vehicle width

When vehicles were equipped with only one tail lamp, they provided no cue to their width. Currently, this is mainly a concern for heavy-duty vehicles and cycles, but passenger cars with only one functional tail lamp, or a single rear fog lamp in fog, are also subject to this problem.

3.3.3. Indication of class of vehicle

At night, the rear lighting system can be an ambiguous source of information about a vehicle's class. If the rear lighting system is fully functional, these problems mainly concern vehicles other than passenger cars. Typical problems of early identification occur with very long, slow moving, or very wide vehicles, and in discriminating two-wheelers from "one-eyed" cars, and mopeds from motorcycles.

3.3.4. Indication of distance to the vehicle

At night, one cue to a vehicle's distance is the separation between the tail lamps. Many researchers have suggested standardization of this separation. In daylight, drivers are reasonably skilled in detecting and estimating forward headway. There, the angular size of the rear of the vehicle and the road area between the lead and following vehicles provide the main distance cues. Mortimer estimated the Weber fraction for distance estimation between cars to be 0.12. This means that if the headway is 100 m, a change of less than 12 m cannot be detected.

3.3.5. Indication of rate of closure to the vehicle

Many researchers consider this variable to be critical in a driver's ability to avoid rear end crashes. The relative velocity or rate of closure is difficult to estimate at long distances. The rate of change of the visual angle of an automobile does not change substantially until the distance is less than about 100 m. For shorter distances, the estimation of rate of closure improves (Mortimer 1997).

In an extensive field test, Parker et al. (1964) evaluated how drivers used three visual cues for estimating approach speed to a lead car ahead at night. The three cues were visual angle between the tail lamps, change in brightness of rear lamps, and change in perceived area of rear lamps. Tests were run at speeds of 32, 48, and 64 km/h. The results show that the three tested factors together give much more accurate results than any factor alone. Visual angle proved to be slightly superior to brightness, and both were superior to area. The approach speed had no influence on the effectiveness of any of the cues.

Reilly et al. (1965) similarly studied the relative importance of these three visual cues, as a driver approaches a lead vehicle at night. Their results showed that a driver uses the angular velocity information from the lead vehicle's two rear lamps, and weighs this information together with his own speed. If the angular separation is distorted (e.g., because of an unusually small distance between rear lights), the driver relies more on change of brightness or apparent size. If the distortion is great, the driver may be incapable of compensating for this, making a closure estimation that is worse than if there were only one rear lamp.

Janssen et al. (1976) investigated the effect of various factors on the movement threshold of a lead car in a series of laboratory and field experiments at night. They found that the relative horizontal angular separation of the lead vehicle's tail lamps is the primary cue for estimating relative vehicle speed. They recommended that the separation between tail lamps be standardized and set as large as possible.

Mortimer (1990) took the analysis one step further. He found that on large distances drivers make judgements of closure to the vehicle ahead of them based on changes in the visual angle. They can detect distance changes as small as 0.12 (Weber ratio) (see Section 3.3.4). However, from vehicle distances of about 130 m or less (dependent on the relative velocity) the importance of rate of change of visual angle gradually increases, and drivers can also give an accurate estimation of the rate of closure. In other words, the driver can detect a closure at large distances, but does not get good information on the rate of closure until the vehicle ahead is fairly close.

3.3.6. Indication of driver intention to brake

The present system provides no prior warning that the brakes will be applied. Several proposals have been presented that offer such information (see Section 4.3).

3.3.7. Indication of the fact that the vehicle is braking (slowing down)

The first problem is to detect brake initiation. In very bright sunlight or extreme glare conditions, the signal is often difficult to detect.

The effect of intensity, area, and aspect ratio on reaction times to brake lamps was studied by Sayer et al. (1996). There is heightened interest in this, as new light sources (e.g., LED) are integrated into the body design (e.g., CHMSLs). Some designs result in very long and narrow signal lights. How does intensity and aspect ratio affect reaction time? The results show that both intensity, and aspect ratio, and their interaction influence reaction time. A combination of a low intensity and a large aspect ratio produces the longest reaction times, and should be avoided.

Brake signals are sometimes masked by other signals. When the brake signal and turn signal are the same color, detection of the brake lamp onset is more difficult. Luoma et al. (1995) concluded that yellow turn signals produced shorter reaction times to the onset of brake lamps than did red turn signals. The difference was in the order of 110 ms.

Brake signals are often confused with rear fog lamps. Helliar-Symons and Irving (1981) found that increasing the separation between the brake and rear fog lamps to 50 mm improved detection of the brake signal. Further improvement at larger separations was limited; nevertheless, they recommended a separation of 100 mm.

The CHMSL was developed to improve detection of the brake signal by separating it from the other rear signals, and positioning it centrally in the visual field of the following driver to make it visible through other vehicles. Crosley and Allen (1966) conducted a study of reaction times with cars equipped with normal and high-mounted brake/tail lamps. In their study, the drivers of the third and fourth cars always reacted quicker when the higher mounted brake/tail lamps were used. The authors recommended that the supplementary brake lamps be mounted high, but tail lamps and regular brake lamps continue to be positioned at their normal mounting height.

Initial accident studies of the effect of CHMSLs in the beginning of the 1980s found an amazing crash reduction effect of about 50%. However, these effects gradually diminished and a recent long-term study (Kahane and Hertz, 1998) suggests a more modest rear end crash reduction of 4.3% with CHMSLs. Nevertheless CHMSLs appear to remain a cost effective crash reduction measure.

3.3.8. *Indicating braking force or deceleration of the driver/vehicle*

The following driver first needs to detect the brake signal, and then needs to decide which level of deceleration to apply to avoid crashing into the lead car. To do this, the driver needs to judge that car's deceleration. Presently, the same rear light signal is produced whether the brakes are lightly touched or heavily stomped on. Drivers are provided little assistance from the brake lights, but several proposals have been made to convey this information (see Section 4.3.).

3.3.9. *Indication that the driver has the intention to stop the vehicle*

The number of rear end crashes occurring when the lead car is stationary suggests that it may be important to know the lead driver's intention to stop. Present rear signaling systems provide no assistance with this, but several proposals have been suggested and evaluated (e.g., Olson, 1989; Shinar, 1995) (see Section 4.3.).

3.3.10. *Indication that the vehicle is stopped*

This is related to the previous problem. Present rear signaling systems offer little assistance, and are sometimes even misleading. For example, vehicles equipped with manual transmissions may be stopped without any brake lights on. Some proposals have been made (see Section 4.3.).

3.3.11. *Indication of driver intention to change forward directions*

Here, failure to use turn signals is the main problem. Mortimer and Domas (1974) found that in urban areas, drivers signaled their intention to turn right only about 50% of the time. Left turns were signaled about 75% of the time. Failure to use turn signals is also frequently observed when changing lanes on freeways.

Fricker and Larsen (1989) argue that, like the use of seat belts, the use of turn signals is a personal choice of the driver and must be enforced to be effective. They suspect that a common personality trait is shared by drivers who fail to use seat belts and who do not use turn signals, and their studies support this hypothesis. Technical solutions are needed to prevent such negligence in both cases.

In certain situations, masking of the turn signals may occur naturally. Sivak et al. (1998) found that sun loading on clear-lens turn signals can reduce the effectiveness of turn signals.

Gibbs conducted two studies of turn signals. In the first one (Gibbs et al., 1952), he compared the British semaphore arm with the U.S. flashing lights. The number of missed signals, reaction time to the signal, and the ease with which the signal was comprehended were measured both in day and night conditions. The possible interaction with brake lamps was also investigated.

The results showed that flashing lights were seen at larger distances than the semaphore arm, especially in adverse weather conditions. On the other hand, the semaphore arm produced shorter reaction times at night, and was less influenced by headlight glare. At shorter distances and in good conditions, the two systems produced comparable results.

In the second study (Gibbs et al., 1955), the effects of flash frequency and flash duration were measured. They found that higher frequencies and brief light durations produced shorter reaction times. Probably as a consequence of the lamps used at that time, they recommended frequencies of 60-120 flashes per minute and an on time to allow the lamp to reach full intensity (about 170 ms). (Some incandescent lamps do not reach their full intensity until about 250 ms after being energized [Flannagan and Sivak, 1988].)

Post (1976) studied the performance requirements for turn and hazard warning lights. His conclusion was that the present standard of 1-2 Hz could be improved if it was increased to 1-3 Hz, because the higher frequencies increase the salience of turn and hazard signals. However, medical studies indicate that for small children, frequencies as low as 3 Hz may trigger epileptic reactions (RRL, 1963). For adults, higher frequencies are needed to trigger epileptic reactions.

Luber and van Elslande (1991) studied the interpretation of turn signals. Their conclusion was that all signals, including turn signals, are interpreted with respect to other circumstances, in particular, the behavior of the other driver. For instance, a driver's speed, changes in speed, position on the road, or change in position independently signal something about the driver's intention. The signal light itself is only one of many cues used.

3.3.12. Indication that the vehicle is changing forward direction (left or right)

During the day, this is less important than the signaling of the intention because in daylight direction is easy to detect. At night this information may be very important. The rear lighting variables are the same as mentioned under Section 3.3.11.

3.3.13. Indication that the vehicle is changing main direction (rearwards)

A back up lamp is one of the vehicle lamps that has a double function. It both illuminates the road for the backing driver, and it signals to other drivers that the car is backing up. Back up lamps work as signals at night but do not offer sufficient illumination. In bright daylight, they are inadequate as signals. No formal studies on back up lamps have been found.

3.3.14. Indication that the vehicle is parked

Prior to World War II, parking lamps were considered very important, but in more recent times, they have become less so. Nevertheless, collisions with parked cars at night continue to be a problem. Presently there are no differences between tail lamps and parking lamps. At night, there is no difference between the rear of a parked car with lights on and a car that is just temporarily stopped. Should there be a difference? The practice of illuminating parked vehicles may have been discontinued because of the energy consumption of parking lights. Modern solutions can substantially reduce energy consumption, eliminating this problem. No formal studies of this problem have been found.

3.3.15. Indication of hazard and/or warning (stopped or moving vehicle)

This function is often misused. Hazard lights also interact with turn and brake lights. Mortimer (1989) pointed out that the interactions between the hazard warning light on one hand, and the turn and brake signals on the other hand have not been analyzed or regulated optimally. This is an example of how new signals are added to the existing signals with not enough regard for the consequences to the overall system. The possible interactions have not been sufficiently analyzed.

3.3.16. Illumination of the license plate

In the early years of rear lighting development, this function was considered very important. License plate illumination was developed at the same time as tail lamps, long before brake lamps and turn signals. Today, it is difficult to understand why this lamp was considered so important. The few studies of license plate legibility suggest that the illumination is less effective than required. It is a difficult task for the lighting engineer to illuminate the whole license plate adequately at a very large angle (almost parallel to the surface) and it causes large problems for lighting designers. At night, when illuminated from a light source close to the observer (e.g., headlamps on another vehicle), retroreflective license plates are normally more legible than when illuminated by a license plate lamp. Exposure to dirt and other forms of degradation of the license plate lamp further impairs its efficiency. Furthermore, it shows white light to the rear, thereby violating one of the conventional rules of vehicle lighting. A radical solution might be to eliminate this lighting requirement. Few would miss it!

4. Discussion: Main Problems and Potential Countermeasures

4.1. General considerations

The ultimate purpose of rear signal lamps is to prevent crashes, primarily rear end crashes but also other relevant types of crashes. These types of crashes are a large and well-recognized traffic safety problem. Consequently, this report focuses on how the rear lamps could mitigate such crashes. To do this, we apply a human factors analysis of the driving task and ask how it may be facilitated or supported by new technological developments and solutions. However, before we discuss how the rear lighting system could be improved, let us look at the problem more generally.

When the interaction between an operator and a machine is not optimal, as is the case with rear lighting, there are four complementary solutions that can be applied:

(1) Only permit expertly trained operators access to the equipment.

(2) Only use equipment that is easy to interact with.

(3) Modify the equipment design to match the competence of the operator (traditionally the task of the human factors specialist).

(4) Train the operator to adapt to the constraints of the equipment.

Of these four alternatives, the first one (of using expert drivers only) is not practical or politically acceptable. The driving population would be as small as the airplane pilot population. Present society depends on the mobility of its population provided by the automobile.

The second alternative (only use equipment that is easy to interact with) is practiced to some extent today. However, opinions vary about ease of use, and the present regulations and standards were largely developed without sufficient regard for human factors. One of the reasons is that regulations and standards are almost by definition obsolete by the time they come into effect. Before we get regulations, research results must be accepted, implemented, and tested on a wide scale. The technology must be accepted by almost all manufacturers. Then comes a lengthy compromise discussion before an agreement is reached. Finally the administrative process and the lead time is time consuming. The history of rear lighting cited earlier illustrates this. Problems are also complex. Often conflicting motives or contradictory research results slow progress. Finally, long-accepted practices are resistant to change.

The third alternative is the approach taken in this report. It is a direct and systematic way of understanding how the human operator, the driver, functions with the car as a system, and it leads to steady improvements in design.

The fourth alternative, use of training, has rarely been discussed. Summala (1998) studied learning of peripheral detection of braking and closing headways. He found no learning effects in the periphery, but left open the possibility of effects in central vision. Drivers appear to have limited success estimating distance, closure rate, and speed change of the car ahead. The extent to which these skills are trainable is unknown. Admittedly, training is not a practical solution for the entire problem of rear end crashes, but it would be of some value to understand more about the limits of acquiring such skills.

4.2. Driver tasks

Lee (1976; 1978) analyzed rear end crashes from a perceptual point of view. First he asserted that driving is predictive. A driver plans what to do next. The driver is attuned to the dynamics of the "optic array" as he drives. Responses are largely automatic. Lee divides the task of approaching a slower moving, stopping, or stationary vehicle into three consecutive parts: detection of closing in, initiation of braking, and regulation of braking force to avoid collision.

The temporal pattern of braking appears crucial. If the braking force is insufficient at the beginning, difficulty escalates. A general recommendation would be to brake hard initially, and adjust the braking force afterwards.

The task of detecting closing in on a forward vehicle, and the task of deciding to brake are performed using visual closure information. Good rear signal lights can be of assistance here. Present brake lamps help support the first task, but not the second one.

Time to collision (TTC) is likely used by drivers to assess the urgency of action. It indicates both the degree of need to start braking and the magnitude of force necessary to avoid a collision. The driver receives feedback about the adequacy of braking from the rate of change of TTC. TTC is also a key measure in car-following behavior at near distances. At greater distances, it appears to be more of a conscious process involving estimation of distance and speed. Thus, behavioral processes in car following can be seen, in different circumstances, as automatic or controlled (see Section 1.1.).

Fancher et al. (1998) found that on limited-access roads with small speed differences and low probabilities of sudden stops, drivers tend to drive with fairly constant headways independent of speed. They found that for speeds greater than 80 km/h, the typical headways on U.S. freeways are just below 30 m, which is amazingly short. The variability increases and the probability for longer headways increases with higher speeds.

Most official driver instructions and recommendations suggest drivers maintain a time gap (time headway) of 2 to 3 s to the car ahead. However, a simple analysis shows that the minimum time gap that a driver needs for reaction time and braking time varies both with his speed and the speed of the car ahead. That is to say, if drivers tend to use a headway independent of speed (which studies indicate that they do), they will have to brake very hard or they will be in trouble when driving at higher speeds or when the car ahead is stationary or moving very slowly. Data from Fancher et al. (1998) indicate that at speeds over about 90 km/h the range of time gaps is very large—from about 0.3 s to more than 3 s. However, the most likely time gap at those speeds was 0.8 s.

A time gap of 5 s would be safe for driving at high speeds, encountering a stationary or very slow moving vehicle ahead, or in bad visibility conditions. Studies show that in real traffic, few drivers maintain such a gap. A British study (cited by Lee, 1978) found that 11% of drivers traveled at headways less than 0.5 s! Fancher et al. (1998) found that more than 10% of time gaps in the U.S. are less than 0.65 s.

The faster the closing velocity, the greater the risk, because the driver has less time to detect and react to the threat of collision. At the same time, a longer braking distance is required (Lee, 1978). Collision risk is also greater the narrower the visible width of the forward vehicle (see also Janssen et al. 1976), because of the difficulty to estimate closure rate. This has implications for the lateral separation of tail and brake lamps.

Lee suggests that the rear of the car including the lamps should be designed so that drivers following another car at night have a stimulus situation comparable to the daylight situation. According to Lee, the brake signal system should include an imperative signal, which is initiated when a following driver *must* brake— i.e., when the car ahead has stopped.

Liebermann et al. (1995) conducted field studies of braking responses to emergency braking. Their conclusions are slightly different from those of Lee. They suggest that braking responses are both automatic and controlled. The presence of brake lamps increases the speed of the braking response. Subjects reacted to the onset of the brake lamps with a "ballistic" braking response. On the other hand, they agree with Lee that the modulation of the braking response is influenced by the optic expansion of the leading vehicle. Consequently, braking responses were faster at short headways.

Ohta (1993) studied the car-following behavior and classified drivers into three groups:

(1) Drivers who attempt to maintain a constant time headway.

(2) Drivers who attempt to maintain a constant distance headway.

(3) Drivers who change their headway depending on the circumstances.

Perhaps, these driver traits can be influenced by changes in vehicle rear lighting. The three groups would probably be influenced to a different degree by training.

Fancher et al. (1998) concluded that the drivers could be divided into five groups:

(1) Ultraconservative (tendency to drive unusually slow and/or with long headways); older and female drivers are overrepresented in this category.

(2) Planner (unusual tendency to drive fast and/or with long headways); male and younger drivers are overrepresented.

(3) Hunter/tailgater (unusual tendency to drive fast and/or with short headways); younger drivers are overrepresented.

(4) Extremist (changes between two of the earlier strategies); the smallest group, fairly equally distributed over age and sex.

(5) Flow conformist (drives as the other drivers in the traffic flow); the largest group, middle aged drivers overrepresented.

Cavallo (1993) agrees with Liebermann et al. in that the improvement of the brake lamps has been excessively driven by the concern to improve detection and reduce reaction time. This view regards the driver as data driven, not a thinking, predictive operator. Cavallo suggests that even if detection is improved and reaction times reduced, if the driver does not improve basic car-following behavior (e.g., by increasing the following distances), there will be little change in safety. Safety improvements can easily be erased by driver compensation or adaptation.

Cavallo argues that studies have shown (e.g., Sivak et al., 1981) that drivers do not brake in slavish response to the brake lamps of the car in front of them. Rather, they regard brake lamps as a warning signal. Drivers often assume that the lead vehicle's braking is moderate and does not require immediate action. While she agrees that early detection is important, she suggests that it is neither the only variable, nor even the most important variable. Cavallo fears that introduction of an advanced warning brake system, for example, that produces false alarms, could adversely affect safety.

For Cavallo, the most important factor to improve safety is to alert the following driver to the unexpected, namely, an extreme slow down or stop of the lead vehicle. As an example, Cavallo mentions the fact that some drivers use hazard warning lights or pump their brakes to provide added warning. Should this be recommended and taught? Cavallo's main conclusion is that many psychological considerations should significantly influence the design of rear lighting systems, and that to date excessive emphasis has been placed on visual considerations.

Colbourne et al. (1978) found that British drivers tend to adopt a headway of approximately 2 s, regardless of speed, driving experience, and instruction. The headways are too short for high speeds, and too long for low speeds.

Evans and Wasielewski (1982) have shown a significant correlation between driving with very short headways (< 1 s) and involvement in crashes and violations. One interpretation is that these drivers have a trait that makes them more vulnerable to crashes. Whether this trait difference is central and cognitive, or peripheral and visual, or both, is unclear.

Van der Horst (1990) tested the hypothesis that TTC is directly used to estimate the degree of risk in a traffic situation, as well as the hypothesis that estimated TTC is based on the optical flow pattern predicted by Lee (1976; 1978). He found that TTC at the onset of braking increases with speed but not as much as it should in order to keep safety constant. When Van der Horst eliminated the optical flow, he found support for the optical flow being used for estimating TTC.

Cavallo et al. (1998) observed car-following behavior in situations with varying degrees of stimulus richness. They found that the more degraded the stimulus situation, the greater the probability of a driver estimation error. This is likely the reason why car following is more difficult in fog and darkness.

4.3. Proposals for improved rear lighting signals

Five U.S. studies performed in the late 1960s (Nickerson et al., 1968; Rockwell and Banasik, 1968; Finch and Horning, 1968; Case et al., 1968, Projector et al., 1969) proposed improvements for rear lighting systems prevalent at that time. One proposal, called a V-bar, involved the use of a large number of lamps to indicate the speed of the car. Another proposal, called AC, used colored lights to indicate the acceleration of the car. A third one presented a distinctive pattern in the rear to signify panic braking, a slow moving vehicle, and a stopped vehicle. A fourth proposal used an array of lamps that changed in number and size to indicate speed changes. None of these alternative designs have been sufficiently tested. However, many of these ideas have been championed by later researchers.

Safford et al. (1970) describes several rear lighting studies. They attempt to determine how to select alternative systems, but without success.

Bol and Decker (1971) suggested several rear lighting improvements to permit better differentiation of the movements of the forward vehicle, including other colors for tail lamps, progressive brake lamps, cleaning systems, and intensity adjustments based on ambient illumination and atmospheric visibility conditions.

Horowitz (1994) characterizes possible improvements of rear signaling systems using five different scenarios, based on accident statistics and human factors considerations. For each scenario, he proposes the use of a particular signal. The scenarios and the proposed signals are listed in Table 15.

Table 15
Suggested improvements by Horowitz (1994) to rear signaling in five scenarios.

Number	Scenario	Signal
1	Braking at low speeds or stopped.	A red flashing signal for stopped or stopping vehicle located in or near the current CHMSL.
2	Deceleration with no braking.	A yellow or red signal for one second.
3	Sudden accelerator release.	A standard brake signal for one second.
4	Antilock braking system activation.	Flashing CHMSL.
5	Braking at any speed.	Improved signal rise time (LED, neon, or fast incandescent) or increased lamp intensity/area.

Jolliffe et al. (1971) argued that the speed of the lead car affects the estimation of closure rate. They noted that drivers infer speed of the lead car using several cues. They suggest the use of a special speed indicator rear light that would simplify the task. To test this hypotheses, they constructed an indicator containing 14 yellow rear lamps in a row. The number of illuminated lamps was directly related to speed. Drivers were asked to estimate closure rate and lead vehicle speed. They report that the speed indicator produces significant overestimation of speed. An important question here is whether speed of the lead car is really an important variable in estimation of closure rate.

Irving and Rutley (1972) tested two driver aids in car following. One was a multilevel brake light, in which a ramp of lamps becomes progressively illuminated as deceleration increases. The second one was a simple head-up display using two vertical lines to indicate the suitable width of a standard car ahead. The separation between the lines varied with the speed of the car so time headway gap was constant. (If the car ahead was wider than the lines, one was following too closely.) Rutley and Mace (1969) found no significant improvement in following behavior with the first aid.

Several researchers have suggested the use of a signal to indicate sharp decelerations (e.g., a variable flashing CHMSL). Although one study supported this concept (Voevodsky, 1974), most studies have concluded that such a device has no or little value (Mortimer and Sturgis, 1974; Rutley and Mace, 1969; Rockwell and Treiterer, 1966; Mortimer, 1981). Goldberg (1997) proposed CHMSL flashes if the deceleration exceeds a threshold, but no relevant empirical data is yet available.

Mortimer and Sturgis (1976) studied the effect of a rear signal that is green when the accelerator is depressed, yellow when it is released, and red when the brake pedal is depressed.

The system was added to a normal rear lighting system. The effects on the behavior of the following driver were only minor, and thus this concept was abandoned.

Mortimer (1971) studied deceleration in the absence of braking signals, when the foot is simply lifted off the accelerator. His results show that the deceleration levels were moderate (0.3-1 m/s^2). He further showed that in most coasting cases, the brakes were never applied. Coasting is usually of a very short duration, and if signaled, should be limited to coasting that exceeds 5 s. Additionally, signaling might be restricted to situations in which the foot is abruptly released from the accelerator.

In a field study of an advanced brake light device (ABLD) triggered by rapid accelerator release, Olson (1989) found that the system produced a highly reliable brake signal following the quick release of the accelerator with few false triggerings of the brake signal. With this device, brake signals can appear 0.2-0.3 s sooner than they do with conventional systems. Olson also estimated the potential crash reduction benefits of an ABLD system. Unfortunately he based this estimation on the comparison with early estimates of the CHMSL effect. Now, with more accurate measures of the crash reduction effect of CHMSL (4.3%), the corresponding estimate of the effect of ABLD is about a 2% reduction in rear end crashes.

Shinar et al. (1997) also studied similar early warning braking systems in which the brake lamps are illuminated for 1 s upon release of the accelerator faster than 0.3 m/s. This reduced the lag in the onset of the brake lights by the movement time of the driver's foot. Like Olson, Shinar (1995) found few false triggerings of the brake signal. In a second study, a simulator was used to mimic the basic characteristics of U.S. highway driving (speeds, headways, road conditions, etc.), so that performance of the system could be evaluated. This specific warning system was found to be most efficient on dry roads when headways were 1 s or less (which is quite common). No differences were found as a function of speed.

In the mid-1970s, LEDs produced only about 1% of the intensity of current units. Nevertheless, lighting engineers hoped to use LEDs in the future because of their long life, fast rise time, low energy consumption, and low thermal properties. LEDs provide uniform luminance and permit flat lamp designs. LED brake lamps first appeared in 1992 in Europe. From the mid-1990s, neon tubes were also introduced in brake lamp applications.

Decker (1999) compared the various light sources now available for rear signaling lamps along several dimensions. LEDs and neon light sources now bid to supercede conventional bulbs in the signal lighting arena. In the future, electroluminescent foils and polymer LEDs may also enter the competition. The market competition has also resulted in many improvements in the performance of conventional bulbs.

Presently, the conventional bulbs are superior in terms of light output for all colors. LEDs are superior in service life and in light efficacy, except for white. Neon light sources, lacking the capability to produce white light, provide illumination uniformity and design versatility.

Masuelli (1995) described present trends in rear lighting. She identified new possibilities afforded by the new light sources, from a design viewpoint.

Sivak et al. (1993) studied reaction time for different types of brake lamps. They found that the reaction time to LED and neon brake lamps averaged 166 ms faster than to conventional brake lamps. A special fast rise incandescent lamp (Flannagan and Sivak, 1988) produced reaction time 135 ms shorter than a conventional incandescent brake lamp. A reduction of the luminous intensity of the conventional lamp from 42 cd to 5 cd resulted in an 84 ms increase in reaction time.

Morrison et al. (1986) found that changing the height of the brake pedal, relative to the accelerator pedal, can reduce the foot movement time by 0.25 s. Gustafsson (1993) proposed to combine the accelerator and brake into one pedal. Toe motion controls the gas, while movements of the foot control the brake. This uses a natural startle response (withdrawing the foot, thereby raising it) for the brake reaction. Furthermore, the foot is always on the pedal. Gustafsson argues that this design can avoid many unintended depressions of the accelerator.

Muth (1999) has designed a supplementary turn signal that is mounted in the side rearview mirrors and visible to the drivers behind.

Finsterer (1995) showed that the hazard warning lights are more readily recognizable if a double pulse system is used instead of the present single pulse. He proposed two pulses of about 170 ms, each separated by an interval of 60 ms. The flashing frequency could vary between 60 and 90 double flashes per minute. Huhn et al. (1997) share this opinion. They note the ambiguity between turn signals and the hazard warning lights because they share the same flash frequency. If one of the two hazard warning lamps is obstructed, it is not possible to distinguish a turn signal from a hazard warning light. Like Finsterer, Huhn et al. suggests that the hazard flashing pattern should be changed to a double flash with a short break.

In the late 1990s, a new concept to increase heavy-truck visibility and identification was introduced: contour marking by means of glass fibers with a central light source (Hella, 1999). Contour marking of heavy trucks by means of retroreflective material has proven effective to reduce night time collisions (Schmidt-Clausen and Finsterer, 1989). It is possible that contour marking of passenger cars would assist in driver estimation of vehicle nighttime distance and motion.

4.4. Ideal and real world situations

At the conclusion of Section 1.3.2., an effort was made to introduce a number of rear lighting issues which deserve additional attention. These issues represent normal road traffic situations that are often not covered by regulations and standards. But normal traffic situations are the situations in which crashes occur. Let us examine how well the present rear lighting system handles these issues.

The balance between adequate daylight visibility and excessive nighttime glare has been largely ignored in present day rear lighting. The ECE regulations permit two intensity levels: one for daylight and one for nighttime. To our knowledge, however, no car manufacturers utilize this option. In the U.S., only one level is specified.

Rear light visibility under reduced visibility conditions, like thick fog or heavy snowfall, is of serious concern. Rear fog lamps, first introduced in the 1960s, attempted to meet this demand. However, we often see cases of one rear fog lamp, reminiscent of the 1940s in U.S., and the 1950s in Europe, when one tail lamp was considered sufficient. No other signal lights (brake, turn, or license) have separate performance requirements for situations with seriously reduced visibility.

Simple car-following situations are rare, because on most roads cars follow each other in long rows. Only CHMSLs attempt to deal with this issue.

Automobile lighting systems have become sensitive optical systems. Rear lamps are exposed to conditions that severely reduce their optical performance. Many rear lamps in actual traffic do not meet the lighting requirements prescribed for them.

Not all road users have perfect vision. Of the male population about 8% suffer from deficient color vision. Furthermore, a significant number of drivers do not have the same vision on the road as when they passed their driver license test. Additionally, the proportion of older drivers with reduced visual capabilities continues to increase (Rumar, 1998). Finally, road users who are not motorists but do participate in traffic, have no visual requirements. There is little evidence that rear signaling development addresses these and related issues.

4.5. Concluding comments

Today's signal lamps are less than optimal, and several design characteristics could be modified to improve driver detection and understanding of their messages. Despite this, it is difficult to satisfy all constraints with a single solution. The research examples and analyses provided characterize both the potential for improvement and the problems that arise in implementation. Rear lamps interact with driving in a complicated way. Proposed changes have to be well justified and supported, because there is much resistance to change in an established system.

During development, a number of factors and limitations have moved the development of rear signaling in specific directions. At times the best solutions were not acceptable or available. Limits on energy availability, light output, optical characteristics, technical factors, or cost precluded their use.

Once a specific system is introduced and widely available, it is difficult and perhaps even dangerous to change it substantially. Often a stable solution is preferred to a technically superior solution.

What should be done? Within the constraints of present technology the following modifications have been proposed by others, and they should be included in discussions of future improvements:

(1) Use of two (or more) levels of intensity of rear lamps: one each for daytime, nighttime, and possibly for low visibility conditions (e.g., fog).

(2) Use of redundancy in encoding messages.

(3) Differentiation between lamps signaling braking and being stopped.

(4) International harmonization of regulations.

(5) Elimination of license plate lamps.

(6) Signaling vehicle type.

(7) Reducing failure rates of lamps.

(8) Redesigning the lamps to reduce the exposure to dirt, corrosion, and damage.

(9) Eliminating driver misuse of rear lamps, especially of turn signals and hazard warning lamps.

Proper car-following behavior should be taught in driver training. Some problems with rear end crashes might be reduced by training.

Modern information technology applications in road traffic—intelligent transportation systems (ITS)—offer new and yet unexplored possibilities to enhance communication between drivers following each other. Those possibilities were not explored here.

Rear end and other relevant crashes constitute a substantial part of vehicle collisions today. They often cause neck injuries. Such injuries often fail to be reported in official crash statistics, but nevertheless cause lifelong impairment and suffering. (It has been estimated that about 25% of all the road crash permanent injuries are caused by rear end crashes.) Improved rear lighting systems would likely reduce rear end crashes and these injuries.

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