Committee Report:
Conspicuity Enhancement for Police Interceptor Rear-end Crash Mitigation

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General Introduction

Police officers are exposed to a variety of hazards in the line of duty. One hazard involves a stopped police vehicle being struck from the rear by an approaching vehicle. Such crashes are rare but not rare enough. A separate report that contains a problem description has been prepared for this Blue Ribbon Panel based on a review of a sample of crash records (Kochhar and Tijerina, 2003). The problem description presents a view of driver, vehicle, and environmental factors associated with such crashes. That report is based on 152 crash records obtained by the Blue Ribbon Panel. It attempts to answer questions like the following: "What was the approaching driver's state?"; "Where was the police vehicle positioned at the time of impact?"; "Were the emergency lights on at the time of impact?"; "What is the role of time-of-day in these types of crashes?"; etc.

The present report complements the problem description. It addresses countermeasures to reduce the incidence or severity of such crashes. This report consists of three sections plus a concluding section that lists recommendations and research needs. The first section is motivated by the fact that driving is largely a visually controlled activity. Visual information that drivers use to steer and accelerate or decelerate is summarized. This summary is then used to suggest visual cues that might be important to avoidance of stopped police-vehicle rear-end collisions.

'Conspicuity' is the term sometimes used to refer to the ability of an object or condition to capture attention (Olson, 1996). The second and third sections of this report address conspicuity from two different perspectives. The second section summarizes the characteristics of police vehicle lighting, markings, and color that increase the likelihood of detection by an oncoming motorist. On the other hand, 'looked but did not see' and 'saw but misperceived' factors that contribute to rear-end crashes in general and stopped police vehicle crashes in particular suggest that making something physically detectable might not always be enough. The third section discusses cognitive conspicuity, defined here as the characteristics of a police vehicle that increase the likelihood not just that it will be detected, but that it will be perceived and reacted to by an approaching driver in a safe manner. This is the least developed area of conspicuity and the one in greatest need of research.

Figure 1 may help put this report into perspective. It depicts the Perception-Decision-Response or PDR process that underlies safe driving and unfolds over time. The process starts with detection, the registration or pickup of information about an object or event. For example, the driver detects that something is up ahead but can't yet make out details. Physical conspicuity addresses factors that make detection more probable earlier in the approach. As the driver approaches, he or she needs to perceive that the 'something' up ahead is a police vehicle, that it is stopped, that it is a certain range, that the approach is at a certain closing rate and trajectory, etc. Visual cues provide the information by which such perceptions arise. Decision includes the
development and evaluation of response alternatives and selection on a course of action. Cognitive conspicuity addresses how expectations shape what alternatives are generated, considered or rejected. Based on the perceived circumstances, the driver must decide on what steering or braking adjustments, if any, are appropriate. Response reflects the driver inputs to vehicle controls to effect the decisions reached. These inputs must be smooth and controlled to maintain safety or else the vehicle may go out of control. Vehicle Response includes the time lag and vehicle responsiveness of the vehicle to driver inputs. This response may be affected by the state of the vehicle as well as environmental conditions such as road surface friction. Vehicle Action is the term used here to refer to the vehicle's trajectory over time up to the successful maneuvering to or around the stopped police vehicle or else to a crash. While the timeline of Figure 1 makes the PDR process appear sequential and linear, there are multiple feedback loops in it that shape the outcome of driving.

We have said what this report contains. It is also important to state what this report does not contain. In the interest of conciseness, it is not an exhaustive literature review. Instead, this report is a summary of research results (when consistent across sources) or listing of controversies (when definitive data are not available or contradictory findings or guidance is contained in the literature), as the reviewed literature dictates. With its emphasis on driver perception rather than sensation, it does not include a discussion of driver vision, though it touches upon relevant aspects of driver vision when necessary (e.g., rod and cone vision in day versus night driving). It does not review specific products. Instead, functional specifications are provided when the literature seems to support such recommendations.

As the analysis by Kochhar and Tijerina (2003) indicates, sometimes approaching drivers notice a parked police vehicle and make a steering or braking input that results in loss of control and a subsequent crash. This is considered at the outset to be a problem of insufficient sight distance for prevailing driving conditions (e.g., lighting, precipitation, road slickness, etc.). The most obvious solution to such crash problems is to modify police procedures to ensure that sufficient sight distance is allowed given the prevailing conditions. The present report therefore does not address aspects of approaching vehicle stability, driver expertise, and other aspects of the latter part of the PDR process. If detection and recognition occur with sufficient time and distance allowed for driver decision and driver-vehicle response, then current vehicle design, driver training, licensing, and the like are sufficient.

The reader of this report may be disappointed that this report does not contain more definitive guidance on how to avoid such crashes. The approach taken is to be definitive when possible, to avoid speculation, and to suggest future research and development. Some of the recommendations are for concepts or systems that have to be tested in the field to determine the extent to which they work. So, recommendations for needed research are also a part of this report. If such research has already been done but was not mentioned here, the authors apologize for the oversight. Indeed, one very tangible benefit of this report may be that others come forward with research and recommendations of their own that address some of the points mentioned here.
References


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**Figure 1.** Perception-Decision-Response Process in Driving.
Part 1:
How Drivers Perceive the Driving Scene and Other Vehicles

By and large, people control their vehicles by looking at the driving scene and making steering, accelerator and braking inputs according to what they perceive. What visual information does the driver depend on to drive safely? What deficiencies in visual perception might lead to crashes in general and rear-end crashes in particular? The answers to these questions lie in what is called the optical flow field (Warren and Wertheim, 1990). In driving, the optical flow field is the optic array of light reflected off of object surfaces and textures in the driving environment (i.e., lane lines, other vehicles, signposts, ground texture, etc.) to the driver's vantage point as the driver looks out the windshield and at the mirrors. As the driver moves, the optic array moves or flows and this visual flow field defines critical information about position, velocity, acceleration, and heading in relation to the world, both for himself and for other objects. A review of visual cues present in the optical flow field will be presented here. By understanding what visual information drivers depend on for safety, concepts may arise regarding improvements to making such cues more conspicuous.

Driving involves a vehicle operator moving through space and observing other objects (vehicles, pedestrians, animals, billboards, intersections, curves, etc.) that may or may not be moving. Driving emphasizes lateral control (i.e., control of lane position, lateral velocity, and lateral acceleration), longitudinal control (control of inter-vehicle separation, vehicle speed, and acceleration/deceleration), and heading control (i.e., control of vehicle angle and angular rate with respect to the road tangent). Piloting an aircraft additionally emphasizes altitude control (i.e., control of vertical position, ascent or descent with respect to the ground), as well as control of aircraft pitch (i.e., nose-up/nose-down rotation about the lateral axis of the aircraft) and roll (i.e., rotation about the long axis of the aircraft). Together these 6 'degrees of freedom' (x-longitudinal, y-lateral, z-vertical, yaw, pitch, roll) define the dimensions of motion in space over time. While we will generally not refer to altitude, pitch, or roll in the discussion of driving that follows, we will make use of terms like heading (i.e., yaw), lateral (y-axis) control, and longitudinal (x-axis) control.

In what follows, the reader may find himself or herself wondering about the descriptions. So much of our perceptions are below our conscious thought processes that we don't really notice such things as will be described below. However, make the effort to consciously attend to the visual stimulation available when driving and many of these points will become intuitively clear.

General Rules of Visually Guided Motion

Gibson (1979, pp. 231-233) has specified the following rules for the visual control of locomotion that apply for driving an automobile (among other applications):

- Starting: To start, make the optic array flow (i.e., set the optical flow field in motion).
• Stopping: To stop, cancel the optical flow.
• Going forward: Make the optical flow field flow outward from the center (this is called outflow)
• Going backward or reversing: To go back, make the flow reverse (this is called inflow)
• Steering: To turn, shift the center of the optical flow field from one patch in the optic array to another. Keep the center of the outflow outside the patches in the optic array that specify barriers, obstacles, and brinks (e.g., ditches) and within a patch that specifies an opening (this is called the field of safe travel)
• Approaching: To approach, magnify a patch in the optic array. To control approach to a solid surface so as to make contact without collision (i.e., stop just at the object surface) move so as to cancel the outward flow of the optic array at the moment when the contour of the object or texture of the surface reaches that angular magnification at which this contact is made.

We can now talk about specific visual information that the driver can use to safely control the vehicle. These visual information cues may indicate deficiencies in perception that might a) contribute to rear-end crashes and b) suggest visually based countermeasures to rear-end collisions.

Where Am I Headed?

Heading direction is visually apparent by that point in the optical flow field (i.e., patch in the optic array) from which the flow of optical texture radiates. This point of radiating texture is the one point in the optical flow field that is not moving. That is where you are headed. When you change heading, the center of the flow field will shift and eventually become centered on another part of the world. That is where you are headed next.

In a dark or textureless field, we may not have a good idea of where we are headed because there are less visual cues than in daylight. Lane lines help us as we drive by providing man-made texture and a track to follow. Contrasting pavement and berm texture or color also helps in this regard. If such road cues are degraded or absent, some potentially critical visual information may not be available to the driver.

Another issue associated with heading is the orienting response. Under certain circumstances such as at night, a driver may indeed see an emergency vehicle with lights on and high visibility markings. That is, the lighting and markings may indeed fulfill their intended function of making the vehicle more conspicuous. However, the lighted vehicle in the distance may become the aim point of the approaching driver (who should be tracking the lane lines instead). That is, the conspicuous vehicle becomes the new focus of expansion or heading direction. This is what is meant here by an orienting response.

How might an orienting response become a crash contributor? It seems implausible given that drivers normally look toward billboards, road signs, buildings, pedestrians, other vehicles, and so forth without veering toward them. There are, however, several reasons why inappropriate orienting might arise that are related to the optical flow field. At night, for
instance, the visual flow field may offer less visual cues than in daylight. At long approach
distances the angular separation between a vehicle in the travel lane and a vehicle adjacent to the
travel lane is visually quite small. Even though the approaching vehicle may not have yet veered
toward the stopped police vehicle, the angular separation might not become apparent or be
detected until too late. As will be seen below, other cues that the vehicle is stopped may not be
available until the approaching driver is dangerously close to the stopped vehicle. The driver's
ability to pick up information from the optical flow field may be further impaired by fatigue,
inattention, alcohol use, or drug use. The orienting response as a crash contributor is a plausible
hypothesis but one that remains to be empirically evaluated. If this is really a crash contributor,
one ironic implication is that an unmarked, unlighted vehicle is less likely to be headed toward
and struck in degraded viewing conditions and probably degraded driver conditions (e.g.,
intoxication, drowsiness) too.

**How Distant is That Object from Me?**

There are a lot of visual indicators to distance that might be used by a driver. The
following list is compiled from Versace (1970), Schmidt (1967), and Schiffman (1976):

- **Visual angle:** Change in size or shape of an object with changing distance (more about
  this later);
- **Linear perspective:** This refers to the apparent convergence of parallel lines, e.g.,
  railroad tracks or lane lines that appear to converge to a vanishing point on the horizon;
- **Texture gradients:** Many objects have a surface structure or "grain". The farther away
  an object, the smaller its details and the more densely packed those details become and
  this gradient of texture provides information on distance. Also, equal spaces appear
  increasingly smaller with increasing depth or distance. Very uniform or homogenous
  road surfaces take away such cues;
- **Interposition:** Near objects partially conceal objects farther away such that the fully
  exposed object appears nearer;
- **Elevation:** The horizon is higher in the vertical dimension of the optical flow field than is
  the foreground. Near objects appear below the eye level while distant objects appear at
  or above eye level.
- **Motion parallax:** Nearer objects are displaced more rapidly than objects farther away as
  the vehicle changes direction (or the driver's head is moved).
- **Aerial perspective or Clearness:** Closer objects appear sharp and distinct while objects
  much farther away appear blurry or less distinct due to dust, water vapor, or other
  particles in the air.
- **Familiarity:** Familiar objects have an expected size and shape based on prior experience.
- **Relative size:** When two similar objects are viewed at the same time, the larger one will
  appear closer.
- **Equidistant tendency:** In the absence of effective distance information, objects that
  appear close to each other will tend to be perceived as equally distant from the viewer.
Other cues might also be mentioned but they are thought to play a less important role in driving. These cues include accommodation (i.e., change in the shape of the lens within the eye), convergence (i.e., tendency of the eyes to turn toward each other while observing very close objects), stereopsis (i.e., the slightly different images in each eye that results from their different vantage points), and brightness constancy (i.e., dimmer objects appear to be further away than the same object at a closer distance). These cues will not be discussed further because they a) either operate only for distances so close or so far as to be unimportant for driving, or b) because they are relatively weak cues as compared to visual angle or motion-based cues.

The information for distance to another object on the ground appears to be related to the amount of texture in a visual angle of the optical flow field. Researchers had observers on an level field of grass move a mobile marker on wheels to a halfway point between themselves and another marker up to 350 yards away (Purdy and Gibson, 1955). People were able to do this fairly well. As Gibson (1979) explains, the number of grass clumps in the farther half of a stretch of distance is the same as the number of the nearer half even though the optical texture of the farther half is denser and more vertically compressed. What remain invariant are equal amounts of texture for equal amounts of terrain.

How Fast Am I Going?

The speedometer tells the driver how fast he or she is going. But drivers don't sample their speedometers nearly so often or so long as they look out the windshield and at mirrors. We depend more heavily on information in the optical flow field to tell us how fast we are traveling. One source of visual information is edge rate, the number of objects in the optic array per unit of time that flow past a fixed point. In driving, the edge rate might be specified by the number of broken white lane lines that pass the edge of the windshield or front bumper per unit of time. Denton (1980) used this principle to reduce approach speed at roundabouts. Denton (1980) gradually shortened the separation of pavement markings (lines drawn across the travel lane) as the distance to the stopping point decreased. At a constant approach speed toward the roundabout the visual impression was that of increasing edge rate, i.e., of speeding up. Research on this treatment indicated that average approach speed to such a roundabout in Britain was lower after the treatment than before and that traffic fatalities also went down.

Beyond edge rate, studies in aviation have indicated that global optical flow rate (i.e., the angular change in texture elements in the optical flow field with respect to the driver's viewpoint) is also a powerful source for velocity information. This work also verified that eyehigh or distance from the ground to the driver's eye point of regard also is important. Basically, the closer one is to the ground, the faster one seems to be traveling for any fixed speed. We have all looked out of aircraft taxing down the runway and gotten an impression of high velocity for takeoff. After takeoff, when we are much higher from the ground, the impression is that we are moving more slowly. In automobile driving, global optical flow rate at a fixed travel speed would be faster for a driver in a low-slung sports car, less for a driver sitting high in an SUV, less still for a driver sitting higher in the cab of a Class 8 truck.
Other information in the optical flow field indicates velocity as well. Objects at different distances move at different velocities. For example, looking out the side window of a moving automobile, one will notice several things. First, the texture closest to the car is moving opposite the direction of travel and faster than objects farther away. Second, objects or texture closest to the driver moves in the direction opposite the direction of driver motion while objects or texture farther way move in the same direction as the driver. A simple illustration of this is provided by Schiffman (1976). Close one eye and hold up two fingers, one about 10 inches in front of the other, in the direct line of sight. Move your head from side to side while maintaining a fixation on the far finger. The image of the far finger will move in the same direction while the near finger will appear to move in the direction opposite to movements of the head. This is an example of what is known as motion parallax.

How Do I Control My Braking?

The imminence of collision with an object is specified in the optical flow field by an explosive rate of magnification called looming (Gibson, 1979, p. 132). If a driver approaches a stopped vehicle ahead at a constant speed, this is accompanied by an accelerated rate of magnification. This explosive rate of magnification called looming has been studied to determine how it might provide time-to-contact information. Optical time-to-contact is called tau and tau at any given point in time of approach is equal to the instantaneous visual angle of an object to the driver's vantage point (in units of radians or degrees of visual angle), divided by angular rate (given in units of radians per second or degrees per second). This ratio yields seconds of time-to-contact. In physical (rather than optical) terms, this equates to range (in meters or feet) divided by range rate (in meters/second or feet/second), the ratio of which also yields seconds to contact. This is currently an area of research and evidence exists that people may use tau, optical expansion rate alone, or some combination of visual angle and expansion rate other than tau (Smith, Flach, Dittman, and Standard, 2001). What is clear is that a) looming is a critical cue to collision, b) to avoid hard contact, looming must be cancelled through braking action or else the driver must steer away from the object.

How Do I Know Closing or Relative Speed?

Drivers sometimes drive into the back of slow-moving vehicles, vehicles stopped in the travel lane, or parked vehicles on the side of the road. These crashes occur when visibility is not a problem and intoxication or health factors are not at play. These types of crashes are often attributed to driver inattention but perceptual deficiencies may be intermingled as well.

Olson (1993) and others have analyzed the difficulties people have in judging closing speed. It was mentioned above that a main cue to distance is the image size an object subtends at the driver's point of view. If the image grows larger, we know the object is coming toward us (if we judge we are at a standoff as indicated by other information in the visual flow field) or we are moving toward it (if so indicated by the information in the visual flow field). The rate of change of object size, looming, has been discussed as a primary cue to control braking.
Perceptual deficiencies in detecting change in object size will contribute to crash risk under certain conditions, e.g., at night.

The rate of change in image size depends on both speed of approach and viewing distance (Olson, 1993). Consider Figure 1, which shows how the visual angle an object subtends at the driver's vantage point changes with viewing distance (See Appendix for explanation). This figure assumes a 6-ft wide vehicle viewed from an initial separation distance of about 1000 ft. The first point to note is that the relationship between object size and distance is highly nonlinear. The second point to note is that the image size of the object does not change much for most of the approach, even though it doubles with every halving of the viewing distance. At 1000 ft, the object subtends about 0.006 radians or one-third of one degree of visual angle. At 500 ft, the image size doubles to about 0.012 radians or two-thirds of one degree of visual angle. At 250 ft it doubles again. Because of this nonlinear relationship, drivers may not realize they are closing in at high speed until quite close to collision.

![Image Size as a Function of Viewing Distance](image.png)

Figure 1. The relationship between image size and viewing distance.

Another aspect of this problem is human sensitivity to various visual information. Visual expansion rate (one aspect of looming) is a key stimulus to detect motion toward an object. Mortimer (1990) has reported that a nominal threshold for visual expansion rate is 0.003 radians/sec. A fully alert driver, then, would only be able to detect that he or she is closing in on a 6-ft-wide stopped vehicle within a certain range, as determined by the following equation (see Appendix for derivation):

$$ R(t)_{threshold} \leq \sqrt{2000 \times Rdot(t) - W^2} $$

where $R(t)_{threshold}$ is the threshold range for detecting visual looming, $Rdot(t)$ is the closing rate (i.e., approaching vehicle travel speed if the other vehicle is stopped), and $W$ is the width of
the vehicle ahead (assumed to be 6 feet in the following figure). This relationship is plotted in Figure 2.

At a closing rate of 60 mph approaching a parked vehicle (i.e., $R_{dot} =$ range rate $= 88$ ft/sec), an alert and attentive driver could perceive (in the absence of other cues) that a 6 ft-wide lead vehicle ($W= 6$ ft) was stopped at a range of approximately 420 ft, or less than 5 seconds of travel time away. This leaves little time for delayed response and maneuvering. Normally, this is a moot point because vehicles ahead are indeed moving or else other factors (e.g., traffic lights, intersections, the movement of vehicles ahead of the vehicle ahead) indicate a standstill. This analysis does, nevertheless, show perceptual limitations that might contribute to such crashes in impoverished viewing conditions.

![Figure 2. Range at which an optical expansion rate threshold of 0.003 radians/s may be detected at various closing rates.](image)

An interesting hypothesis is that ground 'extent' (i.e., the length of pavement between the observer and the object ahead) may also be an effective stimulus for distance and closing rate. Mathematically, image size and ground extent are represented in the same way or are equivalent. However, they offer different means to influence an approaching driver. Image size may suggest treatments to the vehicle, lighting, or markings to induce an approaching driver to slow down or steer away. Ground extent may suggest manipulations of the pavement markings or task lighting to accomplish the same goals.

**Implications**

Crashes are rare events. Drivers often have little experience with the perceptual deficiencies that can cause rear-end crashes. The analysis of visual information needed for driving can provide insights into why people would crash into parked vehicles. It may also
suggest ideas for improved lighting, markings, or other crash countermeasures such as driver education and training.

Consider, for example, the following ideas that emerge from the material just presented:

- **Special warnings** like flashers, flares, warning triangles, and the like are very important for indicating stopped (or slow-moving) vehicles (Olson, 1993). Such special warnings are intended to break up driver expectations of a routine driving environment and prompt a higher level of caution.

- **Looming** is an effective cue to indicate imminence of collision. If the intent of a warning is to send the message 'slow down' or 'steer away', a looming display may be helpful.

- **Lighting mounted high** (on the emergency vehicle roof) may implicate the law of elevation that says more distant objects appear higher in the visual field.

- **With reduced visibility** (e.g., at night, in fog, in heavy rain), lighting that violates expectations based on familiarity might cause illusions in perceived distance. For example, drivers might generally assume that taillights are placed about a car width apart. If a lighting scheme uses red lights placed closer together than normal (e.g., like the closely-spaced tail lights on a bob-tail tractor-trailer rig), the visual impression under impoverished viewing conditions might be that the vehicle is farther away than it really is.

- **Other visual cues** might be presented that manipulate perception of the visual flow field. For example, spiral patterns can induce the impression of expanding or receding depending on the direction of rotation. Such displays have been put to use in aviation cockpit displays of forward velocity (Young, 1968). However, Gregory (1978) points out that if a rotating spiral is stopped, it can induce an aftereffect of apparent motion in the opposite direction.

- **The research of Denton (1980), and others on the impact of pavement markings to affect driving speed** suggests that the visual information regarding the ground extent or approach may also be an useful source of cueing to avoid a rear-end crash. Such concepts manipulate the texture gradient cues on approach to a location.

- **The importance of maintaining pavement markings**, in particular lane lines and edge lines, cannot be understated. Especially at night, such lane markings provide crucial visual information to guide safe travel.

- **The 'moth effect', wherein an otherwise normal driver apparently follows the lights of a parked or stopped vehicle directly into a collision**, is currently little understood. The nature and magnitude of this phenomenon are poorly understood. There are perceptual explanations for how such behavior might arise, as indicated above, but these are only plausible hypotheses that remain to be empirically evaluated. If this is a real concern, it
poses a dilemma. In general, our training, experience, and expectations as drivers suggest conspicuity should improve highway safety. But, if the moth effect or an inappropriate orienting response arose in specific circumstances, an inconspicuous emergency vehicle might be less likely to get hit.

- Reed and Jones (1988) provide an interesting proposal regarding driver training and education. They remark that the relative importance of effortful attention versus perceptual skills in safe driving needs to be worked out. As a leading cause of crashes, driver inattention quickly leads to warnings of the driver's responsibility to be more attentive, more vigilant. Reed and Jones suggest as an alternative that drivers need to be taught safe driving habits, including habits of perception. In particular, they point out the need to teach drivers to attend to what Gibson and Crooks (1938/1988) referred to as the field/zone ratio. This is the ratio of the forward boundary of a field of safe travel and the minimum stopping zone. So, admonishments to 'pay attention' might provide a better result if coupled with 'pay attention to this.' Public service announcements might be helpful to educate drivers about stopped vehicles and the hazards they pose.

References


In Figure 1, visual angle is plotted as a function of viewing distance. At any given time, t, a vehicle of width W, viewed at a distance or range, R(t), from the driver's viewpoint, subtends the following angle, θ(t), (called theta), in radians:

\[ \Theta = \arctan \left( \frac{W}{R(t)} \right) \]

where

θ is visual angle in radians,
W is vehicle width, and
R(t) is viewing distance (in same units of measure as W).

The arctangent function for visual angle is not a linear function of range. However, at longer ranges (and thus smaller visual angles), the small-angle approximation to theta, \( \theta(t) \approx \frac{W}{R(t)} \), is sometimes used and it is linear with range. It is important to use the proper definition of visual angle when considering the full range of viewing distances.

Figure 2 shows minimum distance (i.e., range) to perceive a threshold visual expansion rate of 0.003 radians per second, assuming a given approach speed (Rdot). To obtain angular expansion rate, differentiate visual angle theta (θ) with respect to time to obtain:
\[ \Theta(t) = \frac{-W \cdot Rdot(t)}{R(t)^2 + W^2} \]

To determine the minimum distance, \( R(t) \), to detect the threshold angular expansion rate at a given approach speed (\( Rdot \)), rearrange terms in the preceding equation for a threshold expansion rate, \( \Theta_{\text{threshold}} \):

\[ R(t)^2 + W^2 = \frac{-W \cdot Rdot(t)}{\Theta_{\text{threshold}}} \]

\[ R(t)^2 = \frac{-W \cdot Rdot(t)}{\Theta_{\text{threshold}}} - W^2 \]

\[ R(t)^2 = \frac{-W \cdot \dot{\theta}(t)}{\Theta_{\text{threshold}}} - \frac{\Theta_{\text{threshold}} \cdot W^2}{\Theta_{\text{threshold}}} \]

By setting \( \dot{\theta}_{\text{threshold}} = 0.003 \) radians/second, vehicle width, \( W = 6 \) ft, and treating approaching velocity as negative, the threshold range for detecting looming is:

\[ R_{\text{threshold}} \leq \sqrt{2000 \cdot Rdot(t) - W^2} \]
Part II:
Visual Conspicuity of Emergency Vehicle Lighting Systems and Markings to Avoid Rear-End Stopped Crashes

Introduction

Visual conspicuity refers to the ability of a lighting system or markings to enhance detection by attracting visual attention. Ideally, a vehicle's lighting system or markings will also influence an approaching driver's perception of its identity, distance, and motion (or lack of motion) in such a way as to promote safe driving. In this section, the factors of lighting systems and vehicle markings that influence conspicuity (i.e., detection) and perception will be summarized. See individual references for further details.

The intent of this discussion is to identify lighting configurations and markings that are likely to make stopped emergency vehicles more conspicuous to oncoming drivers and thereby reduce rear-end crashes into stopped emergency vehicles. The lighting that best accomplishes such goals may be different from the kind of lighting that will enhance perception of vehicles in motion. The latter is not discussed here.

It is also important to clarify what message or information the lighting systems and markings should convey. Information regarding, say, the identity of a vehicle as a police vehicle as opposed to a fire department vehicle is not considered. Instead, the following information items are considered the "message" a lighting system and markings need to convey to reduce or avoid rear-end crashes into stopped emergency vehicles. Specifically, the emergency vehicle's lighting should convey the message(s):

- I am present
- I am stopped (a true state) or moving toward you (an illusion that might promote safety)
- Slow down and stay away from me.

General Principles

The following points summarize some key human factors research results regarding conspicuity of emergency vehicles (Code 3, Inc., 2002):

- Objects are likely to pop out and be conspicuous if they are large, very bright relative to their background, if they move or flash, if they suddenly appear, or if they are familiar to us.
- Within reasonable bounds, response time improves with increasing flash rate, flash duration, and brighter lights.
- In order to maintain the same signal range (i.e., range of conspicuity), the intensity of a flashing light will need to be increased over that of a steady light.
- It is the intensity at an observer's eye produced by a light that largely determines if the light will be seen.
The human eye is more sensitive to a light source the closer that source is to the observer's line of sight. This means that the more peripheral a signal is from the line of sight, the brighter it will need to be to gain attention.

Compared to threshold illuminance (where the observer can barely detect the light when directed to look for it), increases of factors of 100 to 1000 are not excessive to attract the attention of an observer not searching for the light.

White light is effective in gaining attention but fails to identify the vehicle. Green is also effective but is a "go" or "safe" color in our society. Yellow, at threshold levels, is often mistaken for a white flash. Red can be easily lost among tail lamps.

In the following sections, different aspects of lighting systems and markings will be examined. Nuances and qualifications to the general principles outlined above will be discussed in the context of a particular factor.

Lighting Factors that influence Conspicuity

Three key factors that affect the visual conspicuity of a vehicle lighting system are a) light output, b) light color, and c) light flash rate or pattern (Smith, 1991). Each of these will be discussed in turn.

**Light Output.** The light output of a light source can influence conspicuity, though in complex ways. If a light source is too dim, a driver may not notice it until it is too late. Beyond a certain brightness, detection remains constant so that increasing the light output doesn't improve detection. In fact, at very high output levels, disability glare would set in and degrade safety. All of these effects depend upon the prevailing illumination, other light sources in the visual field, the driver's light adaptation, etc.

All else being equal, one would think that the light source with the greatest intensity ought to be the most visible. For flashing lights, however, this is not true. For flash durations of up to 100 milliseconds (1/10th of a second), the law of visual perception called Bloch's Law, states that perceived brightness (B) of a light source is the product of light intensity (I) times duration (D), or B=IxD (Schiffman, 1976). Because of Bloch's Law, a light source like a xenon tube that has a much higher light output rating than, say, an incandescent bulb, could appear less bright because of a much shorter flash time. This explains the findings of the Society of Automotive Engineers reported by Smith (1991) that halogen lights were perceived as bright as strobe lights because even thought the halogen lights were 1/20th the peak intensity, they were on 100 times longer than the strobe light's 250 microseconds.

Thus, the total amount of light present with flashing lights depends on product of intensity and duration, not candlepower ratings alone. Our recommendation is to compare alternative lighting systems for their perceived brightness or 'flash energy' as determined by Bloch's Law rather than rely on candlepower ratings alone.

**Light Color.** Light color is also a powerful determiner of visual conspicuity. A key factor related to light color is called transmittance, the amount of light that will pass through a
colored filter or lens. A white filter allows the most light to pass through from a halogen light source. Other colors filter the light source more. For example, amber filters will allow 60% of a halogen light to pass. Red filters will pass about 25% of the light to pass. Blue filters will allow only about 15% of the halogen light to shine through.

Human sensation complicates matters somewhat. At night, sensitivity to blue is greater than sensitivity for red while in daylight sensitivity for red is greater than sensitivity for blue. Smith (1991) reports that with flashing lights, twice the amount of blue light energy is needed in daylight to be perceived as bright as the brightness of a red light. At night, though, the situation is reversed. In night viewing conditions, only about one-third the intensity of a blue light is needed to match the perceived brightness of a red light. So, the sensitivity of the human eye to lighting of different colors depends, at least in part, on the ambient light levels in which those lights are being viewed.

Blue Advancing-Red Receding Illusions: Another aspect of color is that some colors appear to advance and others appear to recede. Luckiesh (1922/1965) points out that, in general, colors whose dominant hues are shorter wave-lengths (e.g., blue or violet) appear advancing toward the observer. Those colors whose dominant hues are longer wave-lengths (e.g., red) appear receding or moving away from the observer. This perceptual illusion is sometimes referred to as blue advancing-red receding.

Research conducted by Berkhout (1979) identified color-based perceptual illusions at night that could have safety implications in driving. In his tests, Berkhout's test participants took 7-second looks at eight (8) different configurations and color combinations of rotating-beam emergency vehicle lighting at night under a variety of conditions. Berkhout's experiment was conducted with observers looking through the windshield of a vehicle parked in the driving lane of an unused gravel road crossing a small river between two bluffs. The vehicle with the lighting on it traveled back and forth on this road at a distance of between 300 meters and 450 meters ahead of the parked observer vehicle. There was no lateral movement of the stimulus vehicle and no other light sources in observer's central 60-degree of field of view other than the stimulus vehicle. The lighting systems were moved toward or away from a stationary observer at rates of 0 (i.e., lighting was at a standstill), 5, or 10 meters/sec at ranges of between 300 and 450 meters. The observers were given 7 second glimpses of the lighting. The lighting systems evaluated were:

- Federal Signal Co. #184: single dome red, center roof mount, 4 sealed beams, 90° separation, 1.75 flashes per second
- Federal Signal Co. #184: single dome blue, center roof mount, , 4 sealed beams, 90° separation, 1.75 flashes per second
- Federal Signal Co. #11: Twin beacon red, 2 sealed beams in each dome, 90° separation, 1.17 meters between lamp centers, 0.87 flashes per second (flashes alternate from side to side at 0.87 flashes per second each, 1.75 flashes per second overall)
- Federal Signal Co. #11: Twin beacon blue, 2 sealed beams in each dome, 90° separation, 1.17 meters between lamp centers, 0.87 flashes per second (flashes alternate from side to side at , at 0.87 flashes per second each, 1.75 flashes per second overall)
• Federal Signal Co. #12: TwinSonic blue, 2 sealed beams in each housing, 180° separation, 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 3.50 flashes per second overall
• Federal Signal Co. #12: TwinSonic red, 2 sealed beams in each housing, 180° separation, 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 3.50 flashes per second overall
• Federal Signal Co. #12: TwinsSonic red right/blue left, front view, 1.12 meters separation between lamp centers, 0.87 flashes per second (front view), 0.87 flashes per second overall
• Federal Signal Co. #12: TwinsSonic red right/blue left, rear view, 1.12 meters separation between lamp centers, 0.87 flashes per second (rear view), 0.87 flashes per second overall

Berkhout's results for perception of motion were interesting and complex. Table 1 presents the judgments for those trials where the lighting system-equipped vehicle was actually stationary or parked. The first point to note is that when the lights were stationary, percentages of responses correctly indicating the lighting was not moving were all under 50%. That is, observers reported the lights were moving in more than half of the trials. The TwinBeacon (alternating side-by-side) red lighting produced the worst illusions of a stopped vehicle moving away or receding from the observer with 55% of all responses making this mistake. For vehicles parked on the shoulder of a road and displaying this light, Berkhout suggests that there would be an increased risk of rear-end collision. This provides some evidence for a red-receding illusion.

When the lighting vehicle was parked, the single dome blue and TwinSonic blue lighting systems also produced 30% and 27% erroneous responses of the 'moving away or receding' variety, respectively. On the other hand, the TwinSonic blue lighting, single dome blue, and three blue lights together creating the strongest illusion of an objectively stationary lighting system moving toward or advancing on the observer with 31%, 26%, and 26% of responses in error respectively. The table shows almost the same percentages of "toward" and "away" judgments for many lighting configurations, which might be interpreted as confusion and chance guessing. Overall, the results do not show as strong a set of evidence for a "blue advancing" phenomenon. Both 'red receding' and 'blue advancing' phenomena are subject to substantial individual differences. Direction of motion perception is quite poor in the conditions of this study, regardless of lighting systems and direction of motion. There is some cause of concern that red lighting under certain night time conditions would be perceived as a vehicle in motion away from the observer, but this is not uniform nor are blue lights immune from such misperceptions.
Table 1. Percent Responses (N=78) For Stationary Lighting Systems (Source: Berkhout, 1979).

<table>
<thead>
<tr>
<th>Light System</th>
<th>Moving Towards</th>
<th>Still (Stopped)</th>
<th>Moving Away</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Dome (Red)</td>
<td>17</td>
<td>47</td>
<td>36</td>
</tr>
<tr>
<td>TwinSonic (Red)</td>
<td>16</td>
<td>46</td>
<td>38</td>
</tr>
<tr>
<td>Single Dome (Blue)</td>
<td>26</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>TwinSonic (B+R; rear)</td>
<td>20</td>
<td>44</td>
<td>36</td>
</tr>
<tr>
<td>TwinSonic (Blue)</td>
<td>31</td>
<td>42</td>
<td>27</td>
</tr>
<tr>
<td>TwinSonic(B+R; front)</td>
<td>24</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Twin Beacon (Blue)</td>
<td>20</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>Twin Beacon (Red)</td>
<td>9</td>
<td>36</td>
<td>55</td>
</tr>
<tr>
<td>3 Blue Lights Together</td>
<td>26</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>3 Red Lights Together</td>
<td>14</td>
<td>43</td>
<td>43</td>
</tr>
</tbody>
</table>

Note: Still (i.e., Stopped) responses are correct. Light systems are listed in order of percent correct.

Taken together, these studies have several implications. First, red-only alternating side-by-side lighting is a poor choice for night-time warnings of an emergency vehicle stopped on the roadway or berm. Red-receding illusory motion for a parked vehicle is of particular concern for safety. Second, blue-only lighting will be more conspicuous (due to human visual sensitivity at night) than red lighting at night, though the reverse holds for daylight conditions. Third, blue lighting sometimes leads to an impression of a stopped vehicle advancing toward the stationary observer, but can also be associated with an illusion of receding. Thus, blue is also not a good cue for motion (or lack thereof.). Combining the two lights into a lighting system has some advantages. Bicolor (red and blue) lighting has been successful in reducing rear-end collisions with stationary vehicles (Pudinski, 1974). However, the perceived intensity differences of bicolor lighting have made it difficult for observers to perceive them as equidistant from the observer. Headlight glare has also washed out the blue lighting more than the red and this too led to a perception of the lights being located at different distances. In total, to help prevent rear-end collisions with stopped emergency vehicles under night conditions and to accommodate visual sensitivity under day light and night conditions, bi-color lighting is recommended. But it should not be expected that this lighting by itself will provide good cues to motion.

Some mention of the 'meaning' of different colors is in order. In American culture, red means 'danger' or 'caution' and, in the driving context, 'stop', 'stopping' or 'prepare to stop' according to a survey of motorists by the Texas Department of Transportation (Ullman and Lewis, 1998?). Smith (1991) points out that, depending on jurisdiction, blue may indicate 'emergency vehicle', while amber typically indicates 'yield or prepare to yield'. He suggests that amber lights be sequenced to generate an arrow to direct traffic in a specific direction. Wells (1999) points out that red beacons might be confused with tail lights.

The conspicuity of a lighting system will depend, at least in part, on the color contrast between the lighting and its surround or background. A setting sun with deep reds will tend to make red lighting less noticeable. Bright sunlight and strobe lights have similar color
temperatures, suggesting that strobe lighting might blend with the daylight and therefore appear dim in bright daylight. Also, the color effects reported by Berkhout (1979) may not hold for lighting with less saturation or purity and might be more pronounced with lighting of greater saturation or purity.

**Flash Rates.** Motion is an especially effective stimulus in the visual periphery. Central vision is of a small area (1 to 2 degrees of visual angle), very high-resolution, and (normally) full color vision. Peripheral vision is of progressively lower resolution or detail, with color vision dropping from full color in central vision to sensitivity for yellow and blue out to 40 to 50 degrees from a central fixation point, and finally to black-and-white vision beyond about 60 degrees in the periphery. The rods that make up the receptors in the visual periphery are many times more sensitive to blue light than to red light, regardless of the color perception. The loss of color vision and detail in peripheral vision is made up for by greater sensitivity to movement, including flashing or blinking. This suggests that for maximum impact, high-intensity flashing lights will capture attention even if the light source is off-axis from the driver's line of sight.

One concern that has been voiced about flashing lights is that they may induce nausea or epilepsy in some observers; this term is called 'photic driving' (Schiffman, 1976). The phenomenon is real enough and is used as a routine laboratory procedure to induce epilepsy in certain individuals, generally in the 6 to 40 Hz range, faster than typical emergency vehicle devices. De Lorenzo and Eilers (1991), a pair of physicians, report that there are no data to support a seizure risk with strobe light in emergency vehicle applications.

Smith (1991) points out that there are several advantages to rotating lights as opposed to flashing lights. If the light is rotated rather than turned on and off, this achieves the attention-getting effect of flashing but also provides continuous light output in all directions. This allows other drivers from all directions to see the stopped vehicle. The continuous light output also reflects off of the ground and other objects to increase conspicuity. Solomon (1999) considers a slowly rotating beacon a common sense approach to using warning lights. Solomon generally advocates that emergency vehicles be equipped with fewer lights that flash less rapidly (no flash rate recommendation provided) and less brightly, and that convey a minimum number of messages.

ICE Ergonomics (2002) recently provided some guidance on flash rates based on both laboratory and field work. The primary method used involved ratings, so the data should be interpreted with caution. Ratings or conspicuity and actual detection performance are not necessarily the same thing. The report indicates the following. First, strobe (flash) warning beacons convey greater urgency but rotating beacons were considered less annoying and minimized effects of disability glare (at night). High flash rates of 4 Hz (240 flashes per minute) are better at conveying urgency (day or night). Low flash rates of 1 Hz (60 flashes per minute) minimize discomfort glare (day or night), disability glare (night), and perceived annoyance (day and night). With more than one beacon, beacons flashed simultaneously were detected significantly more quickly than those that flashed alternately. Multiple beacons were rated as more attention-getting than a single beacon, with 4 beacons rated higher than 1 beacon but less than 8 beacons. The report concludes with a recommendation for road trials.
In summary, the flash rates used in emergency vehicle beacons are generally not in the range of concern for inducing epilepsy. More flashes per minute generally imply higher conspicuity, but this is also associated with higher glare and annoyance. Multiple beacons increase attention-getting but at the cost of annoyance. It is unclear how ratings of conspicuity would relate to actual driver detection and response performance.

**Luminaire Types:** Code 3, Inc. (2002) indicates that there is no basis to prefer one type of lighting to another. Smith (1991), on the other hand, points out that strobe lighting can be less effectively bright than halogen lamps, that halogen color temperature is more compatible with colored lenses, and that strobe lighting's color temperature can blend in with daylight, reducing conspicuity. Beyond this, strobe lighting can create a stop-action effect that creates ambiguity regarding a vehicle's motion or lack of motion, among other illusions. LEDs offer great versatility, long life, high light output, and low maintenance, but they tend to be highly directional. This latter feature should be of no concern for vehicles approaching a stopped emergency vehicle from a distant, straight approach or for rotating beacons. On the other hand, LEDs may be less conspicuous when viewed at an angle.

**Vehicle Color and Markings and Conspicuity**

It seems plausible that vehicle color can affect visual conspicuity. Allen (1970) reported insurance studies that demonstrated fewer automobile collisions with white or yellow cars. It is not known whether this is truly an effect of color or instead that color is confounded with other factors that really underlie the crash experience. For example, more aggressive drivers (e.g., younger males) may favor red or black vehicles while more cautious drivers (e.g., parents, older persons) favor white or yellow vehicles. Still, other research on driver vision has reported that cream, yellow, and white objects are most visible on the highway (Hills, 1980; Birren, 1957).

Consistent with the previously noted findings, Solomon (1990) has advocated for the use of lime-yellow color to make emergency vehicles more conspicuous. He bases his recommendations on a study he conducted comparing the number of collisions that occurred with fire departments with red vehicles as compared with fire departments with lime-yellow vehicles across nine fire departments. The results of this study showed that the lime-yellow vehicles had a collision rate less than half that of the red vehicles. More recently, Solomon and King (1999) have pointed out that peripheral or off-center vision is most often responsible for early detection and that lime-yellow is seen significantly faster (earlier) than red in a peripheral view. Solomon's recommendations have been taken up by many fire departments, though less so by police departments.

Color variations are also intended to enhance conspicuity. National Highway Traffic Safety Administration (NHTSA, 1985) specifications for ambulances dictate that the ambulance be painted white with a horizontal orange stripe and blue lettering. In urban environments, this color selection may be less conspicuous than, say, the lime-yellow color scheme.

Rubin and Hewitt (1981) recommended a harlequin pattern for emergency (police) vehicles to enhance their conspicuity. In Europe, two-color chevron patterns applied to the back
of emergency vehicles are intended to reduce the incidence or rear-end collisions. A wide variety of color combinations have been used. Though lime-yellow and orange appear to be a popular combination in the UK, any strong contrasting color scheme may be equally effective. Figure 1 illustrates three versions of the rear-end chevron pattern. Note the impression of a barrier that this pattern makes. There is a need to evaluate the effectiveness of such markings on rear-end crash prevention. One potentially useful variation on the rear-end chevron markings concept is to deploy the markings only when stopped so that drivers learn to associate such patterns only with stopped vehicles. Various technical implementation of the when-stopped-only rear-end chevron marking are possible but whether these are necessary remains for a field study to determine.

Figure 1. Rear-end Chevron patterns for police vehicles in three color schemes. (Source: Wells, 2002)

The main problem with any multi-color markings is that instead of enhancing conspicuity, they may in fact reduce it. As indicated in Figure 2, some patterns may effectively serve as camouflage by breaking up the outline of the vehicle and making it appear less like a vehicle. Recently, Langham and Rillie (2002) have recommended uniform color rather than a harlequin or Battenburg Livery pattern that might disrupt the percept of the vehicle as a whole. Research is needed to determine the effectiveness of chevrons, harlequin patterns, and other treatments.

Figure 2. Harlequin or Battenburg Livery markings raise concerns about camouflage effects. (Source: Fay and Sferco, 2002).
On the other hand, retro reflective markings that demarcate the outline of the vehicle should, in principle, enhance conspicuity (Langham and Rillie, 2002, Green, 1977, Solomon, 1999). Retro reflective markings have been quite effective in enhancing truck conspicuity and reducing the incidence of collisions with trucks at intersections and elsewhere. Edge markings or demarcation appear to be the most appropriate or important effect to be achieved. An example of such retro reflective markings and uniform color prepared by the Transport Research Laboratory in England is provided in Figure 3.

Figure 3. Retro reflective edge markings and uniform color intended to enhance vehicle conspicuity (Source: Fay and Sferco, 2002).

Recommendations on vehicle color and markings might be summarized as follows. White, crème, yellow, or lime – yellow vehicles might be more conspicuous than other colors in vehicles (red, orange, blue, black) but additional research is needed in this area. Rear-end chevron patterns may serve as useful conspicuity enhancements for emergency vehicles but the actual safety benefits are unknown. Similarly, Battenburg Livery or harlequin markings on emergency vehicle bodies are also intended to enhance conspicuity but may in fact break up the percept of the vehicle and make it less identifiable. Unfortunately, no definitive studies have been found that compare crash rates for these markings and other vehicle options, controlling for exposure factors and or nuisance variables. Careful research is needed to determine whether putative benefits are truly due to the color and markings rather than to other factors. Furthermore, research is needed to determine if markings intended to enhance conspicuity do not, ironically, serve to camouflage the vehicle instead. The backgrounds against which emergency vehicles operate is also a critical concern. A crème color vehicle may be quite conspicuous against dark pavement, yet blend into a desert background.

Highway Flares and Conspicuity

Solomon (1999, pp. 75-79) points out that highway flares, while not part of an emergency vehicle, are often used along side it with the intention of enhancing conspicuity. However, flares may ignite flammable materials nearby, may generate so much smoke that the flare obscures rather than renders more conspicuous, and provide a flickering light source on the road that
distracts the approaching driver from the emergency vehicle itself. Together, Solomon suggests, these factors may actually contribute to emergency vehicle camouflage rather than to conspicuity. He acknowledges a lack of scientific data on such factors and cautions against inaccurate assumptions behind flare use (and other conspicuity enhancements).

In Part II, lane lines were mentioned as important to support visual control of driving. Figure 4 presents a concept of flare use that builds on this observation. The idea is to create a directed path that will direct approaching motorists away from the stopped emergency vehicle. Flares might be deployed in such a manner as to create a 'virtual runway' that directs traffic away from the stopped police vehicle in a safe and efficient manner. This concept is untested (to the authors' knowledge), has practical issues to overcome (e.g., approaching vehicles may run over the flares and put them out or move them out of position), and may have unintended consequences (e.g., may confuse drivers under certain circumstances). Research is needed to refine and evaluate the this and other concepts presented in this report.

![Figure 4. Flares used to create a 'virtual runway'.](image)

**Retro reflective or High Visibility Vests**

A pedestrian by the side of the road is generally noteworthy. It may also seem unlikely that a moving vehicle would be adjacent to a standing pedestrian, thus making the stationary state of the vehicle more cognitively noticeable. On the face of it, then, treatments that increase the conspicuity of a police officer or other pedestrian on the side of the road beside a stopped emergency vehicle ought to be of general benefit. High visibility clothing in the UK, for instance, is not simply retro reflective. It aims to give a high level of conspicuity in normal day light and limited light/bad weather as well as having highly reflective elements which work when wet (a lot of reflective clothing apparently doesn't!). A European Standard (EN471) that
includes differing specification classes covers its specification. Figure 5 depicts one version of highly reflective clothing.

Figure 5. Retro reflective outer wear to enhance pedestrian conspicuity.

From the operational standpoint, the circumstances are not so straightforward. Wells (2002, personal communication) points out that officers often do use reflective and hi-visibility vests now, but only on longer incidents such as crashes or traffic direction. In Florida, state police are currently moving to a vest that meets the new ANSI standard, but it may not be possible to meet level 3 (highest level of visibility) because it would require pants as well as a vest/coat. One difficulty is that officers can't cover the uniform belt and hinder access to equipment. Also, some departments will advise officers not to use retro reflective or high visibility gear at night, at least for traffic stops. This is to reduce the risk of being seen, and possibly shot at, upon first approach. This compromise between conspicuity and others types of threats must be discussed and assessed in terms of the costs and benefits of each alternative.

Implications

Based on the literature reviewed, the following recommendations and functional specifications regarding lighting systems and vehicle markings are offered to enhance the conspicuity of a police vehicle:

- Emergency Lighting Systems are characterized by their light sources, light output, light color, and flash rates:
  - Luminaire Type: No specific recommendations for light sources (e.g., halogen, strobe, LED) are offered at this point.
o Light Output: Compare alternative lighting systems by inspection for their perceived brightness or 'flash energy' as determined by Bloch's Law rather than rely on candlepower ratings alone;

o Light Color: Amber lenses pass greater light than red or blue lenses and so can be quite visible. Amber generally means 'yield.' However, amber lights might be less visible under certain daylight conditions and can be glaring under nighttime viewing conditions. Red lights signal 'stop' and are more readily detected in daylight than blue lights. They may also be confused with red tail lights in surrounding traffic, can be masked somewhat at dusk by a red sky, and can induce a moving-away illusion when stationary and viewed in darkness. Blue lights are more visible than red lights in dark viewing conditions and may be less glaring than amber lights at night. But, blue lights are not reliable indicators of motion or lack of motion at night. To promote conspicuity in various day and night viewing conditions, multi-color lighting is recommended. For example, the common red-blue combination of lights may be augmented by amber lights sequenced to generate an arrow to direct traffic around the stopped emergency vehicle (Smith, 1991). Note that some authorities have expressed concern that too much emergency lighting is potentially confusing (Solomon, 1999). A field comparison of different lighting systems' complexity would be helpful in empirically resolving this issue.

o Flashing lights and Flash Rates: Flashing lights are more easily detected in the visual periphery than a constantly glowing light. A rotating beacon can be more conspicuous than a flashing (ON-OFF) light. Use flash rates slower than the 6 to 40 flashes per second range (i.e., 360 flashes per minute to 2400 flashes per minute) to minimize the possibility of triggering epilepsy in susceptible persons. Higher flash rates (4 Hz or 240 flashes per minute) signal greater urgency than slower flash rates (1 Hz or 60 flashes per minute) but are also more annoying. Multiple beacons (e.g., 4 beacons) are rated as more attention getting than single beacons.

- Markings: At present there is a need for field data to determine the effectiveness of various markings. However, theory and inspection suggest that the following may be useful in enhancement of emergency vehicle conspicuity:

  o Avoid markings or color schemes (e.g., Battenburg livery patterns) that break up the contours of the vehicle and so may actually act as camouflage;

  o Consider rear-end chevron patterns that consist of high-contrast colors and convey the impression of a barrier;

  o Consider markings that demarcate or outline the body of the vehicle.
• High visibility vests or outer wear may increase pedestrian officer conspicuity and so alert the approaching motorist to exercise extra caution. However, this must be weighed against other safety and security concerns such as risk of being fired upon.

• Some authorities stress the importance of flares as indicators of an emergency or presence of stopped vehicles. Other authorities claim that the flares are a potential distraction in their own right. Evidence for the latter was not found in the reviewed literature while operational experience suggests benefits to flares.

There are many research issues in the area of emergency vehicle lighting, markings, and vehicle color. Perhaps the greatest area of need is in experiments and field studies that compare safety across different types of physical conspicuity treatments. For example, attempts were made without success to obtain British research results on the effectiveness of emergency vehicle rear-end chevron markings on emergency vehicles in the UK. Such field experience would be quite valuable if both research and analysis were properly conducted. Similarly, an analysis of the rear-end crash experience of maintenance vehicles with amber lighting and directional arrows would be instructive. A comparative field study of the impact of police vehicle color would also be a useful follow-on to the lime-yellow fire truck research of Solomon (1990).

References


Part III:
Cognitive Conspicuity and Its Role in Rear-end Police Vehicle Crashes

Introduction

It may seem odd that police vehicles, marked and lighted to be conspicuous, should be struck from behind while stopped. However, USDOT statistics (Knipling, Wang, and Yin, 1993) for police-reported rear-end crashes in the General Estimates System indicate approximately 1.5 million police-reported crashes in the United States, 70% of which involved a stopped lead vehicle. The majority of these crashes are in daylight, dry pavement conditions, i.e., conditions of good visibility. The majority of these crashes involve drivers who are not intoxicated, who do not report being fatigued or asleep, and who are not otherwise incapacitated. Crash records also indicate that drivers in rear-end crashes often make no precrash avoidance maneuver (braking or steering prior to contact). While analyses of subsequent years have resulted in variations in these statistics, the stopped lead vehicle rear-end crash remains as a common subtype.

Charles, Crank, and Falcone (1990) examined roadside crashes in the state of Illinois. According to their executive summary, the normative conditions for such roadside crashes are good weather, clear roads, dry driving conditions, and unimpaired drivers of striking vehicles driving on a straight section of roadway. Police vehicles are the most likely to be struck of four emergency vehicle types (police, ambulance, fire, and other), perhaps because there are more of them on the road at any given time. Police vehicles are also physically the smallest of the emergency vehicles and may have less lighting overall than other emergency vehicle types. Despite light bars and precautionary training, Charles et al. (1990) indicate the number of police roadside accidents at night is proportionally similar to the number of passenger car accidents (presumably also roadside). No mention is made about corrections for exposure. However, the general picture is one of normal drivers running into conspicuous vehicles for undetermined reasons.

Stoica (1984) reported on a comparative study of marked and semi-marked police vehicles in Illinois. This comparison involved the 1982 crash experience of 56 semi marked units as compared with the 1980 crash experience of 741 marked units. The comparison showed 5 of the 56 semi marked units (9%) involved in a crash as compared with 199 out of 741 marked units involved in a crash (27%). This study must be interpreted with caution given the large number of variables that could have affected the results. Among these factors are the differences in years, the fact that the substantially larger fleet of marked vehicles (larger by a factor of 13) may have been exposed to a wider variety of hazards, and may have been driven by a broader range of officer experience. Furthermore, the crash involvement was not confined to rear-end crashes, nor was the data conditional on lights being used versus not used.

The Illinois state police crash experience was later examined by Raub (1985). He looked at crash involvement of police patrol vehicles with roof-mounted lights as compared to police
vehicles with lights removed. Among the results of the comparison were that police vehicle accidents (not necessarily roadside-parked vehicle accidents) were higher with marked vehicles than with unmarked vehicles. This comparison held after equating for driver safety records. Raub suggests that semi-marked police cars are safer because officers assume that roof-mounted emergency lights project unchallenged authority. When the light bars are removed, an officer has to become a more cautious driver. However, no data on this particular hypothesis is included in the paper. This study, like the Stoica (1984) research, is subject to many of the same cautions.

Lest one go away with the impression that the paradoxical safety results of conspicuity reported by Stoica and Raub are the final word, other researchers have reported no differences between vehicles with lights and markings and those without. For example, the 'mosquito effect' (also called the 'moth effect') is a theory that motorists are drawn to emergency warning lights that catch their attention. According to this theory, and the warning lights actually contribute to crashes. According to Wells (1999), the president of the Florida Highway Patrol Chapter of the Police Benevolent Association Commissioned a study to examine the extent to which this theory might be borne out in the crash record. No such evidence was found. In a separate study by the Illinois State Police of 120 rear-end collisions into marked vs. unmarked patrol cars, also reported in Wells (1999), there was no increase in the rate of these collisions for marked cars. Similar results have been reported elsewhere, e.g., Davis (1982).

It is sometimes the case that a person will not see something, or will not see something change, even when looking at it. This is sometimes referred to as 'inattention blindness' (Mack and Rock, 2000) or "change detection blindness" (Resnick, 2002). In automotive safety, there has long been a category of factors contributing to a crash called "looked but did not see." Research on 'looked but did not see' crashes is reviewed by Langham, Hole, Edwards, and O'Neil (2002), particularly crashes in the UK involving stationary police vehicles. Based on a set of 47 such collisions, after removing driver impairment, fatigue, poor weather, and the presence of obstructions, 29 cases remained for a clearly conspicuous police vehicle being struck by an apparently normal driver who claimed not to have seen the vehicle at all or at least not in time to avoid the crash. The police vehicle was parked 'in-line' with the travel lane 59% of the time but in the other reports the orientation is not explicitly mentioned. Early deployment of warning signs and traffic cones did not guarantee detection. Some 65% of these crashes occurred within 15 km of the striking vehicle driver's home address. The offending drivers were over age 25 year except in one case. In almost 40% of the cases, the offending driver did not attempt to brake at all before the collision and 70% of driver comments indicated, "I didn't see it." Taken together, these results suggest that perceptual and cognitive factors may play a large role in such crashes.

Cognitive Bases for "Looked But Did Not See" Crashes

Barring intoxication, illness, drowsiness, road rage, or other anomalous states, the average person does not intend to drive in such a way that personal injury (either to themselves or others) or property damage (either to their own property or that of others) result. It is easy to read an account of a crash with seemingly reckless behavior and conclude that the driver was obviously crazy or irresponsible (or both). However, this assumes that hindsight is equal to
foresight. It is more reasonable to believe that people behave according to their situational understanding and motivations at the time. That is, they behave with bounded rationality or limited rationality. People also routinely select what they will pay attention to from a much broader range of options.

**Driver Expectancies or Schemas.** Gibson (1966, pp. 309-310) puts the matter into common sense perspective. The driving environment generally provides more sights than the driver can register at once and so he or she must be selective. The number of different objects in different directions might be huge and no one can look at them all... too many things happening too fast to comprehend them all. In the face of this over stimulation, the driver develops an economical strategy of perception. As Gibson (1966) explains, after things are discriminated and their properties are abstracted, their number is reduced to a few categories of interest and much of the rest is neglected. When the driver takes a glance, he or she neglects available information according to the driver's expectations or schema. The danger in such a strategy is that an object may be important and exceptional but not in one of the driver's categories of interest. What that object may afford the driver by way of, say, threat information is missed or what the driver perceives may be mistaken. So, the danger of a schema or skeletonized prejudgment of what is important is that the prejudgments are not elaborate enough. Usually, they are quite adequate and this adds confidence that all is as the driver expects. To paraphrase Will Rogers: "It ain't what you know that's so bad, it's what you know that ain't so."

What we perceive, then, is strongly driven by our current understanding of and assumptions about the world. There is so much information potentially available to the driver that drivers attune themselves to those cues that are most appropriate to their interests and knowledge about the current situation (Gibson, 1966). The term "schema" has been used to describe this current understanding, set of assumptions and expectancies. The schema may initially be heavily data-driven. Sensory cues shape the current schema by a bottom-up process. For example, the driver initially looks to the mirrors and the road scene ahead to check for surrounding traffic or vehicles ahead. However, once initial values are set, it often becomes the case that the driver's perception is then increasingly conceptually driven. That is, the schema directs visual sampling, processing, and decision making in top-down process. The driver processes cues from the driving scene or mirrors and makes sense of them based on the current understanding of the situation (schema). The schema then begins to control what elements of the driving situation are sampled and how they are interpreted. After a while, the driver may sample mirrors less frequently because he "knows" that there is no one beside him (most lane change crashes involve vehicles in the blind spot) or because he "knows" that this is a highway and the vehicles ahead of him are moving (most rear-end crashes involved lead vehicles that are either stopped or moving very slowly when struck).

**Cognitive Biases.** There are a variety of biases in human cognition that lead to seemingly irrational behavior. A "salience bias" may arise because, based on the current schema, only a small number of cues are focused on even though others may objectively be more critical or necessary to guide action (Wickens and Hollands, 2000). For example, a driver on an open highway may notice a slow-moving vehicle ahead (a salient cue) but fail to notice in the mirror a motorcyclist has entered the roadway and is closing from behind (an important, but unnoticed cue). The driver may then make a lane change to overtake the slow-moving lead
vehicle without sufficiently checking the adjacent lane. Safety is clearly compromised if the motorcyclist is in that adjacent lane.

Perception is largely determined not by physical characteristics, but by the perceiver's intentions and goals. While it seems reasonable to assume that emergency flashers would "break through" an inappropriate schema, there is still an "as-if" bias that people hold. For example, the driver may behave "as-if" the parked police vehicle is actually moving in pursuit rather than stopped. It is often the case in driver distraction crashes that the driver behaved "as-if" there were nothing ahead on the roadway to be concerned about.

A related bias in human cognition is called the confirmation bias. This bias causes people to seek out information that confirms their expectations and ignore disconfirming evidence. Thus, a driver will seek to affirm, not falsify, his or her understanding of the driving conditions in order to conserve effort or allocate their efforts to thinking about or doing other things. If a driver believes that there are no vehicles in the vicinity (because there usually are not) or that vehicles up ahead are moving (because they usually are), then the driver may sample the road scene in such a way that critical cues to stopped traffic ahead are ignored or processed too late.

One other relevant bias in cognition is the 'representativeness' bias. People try to understand a current situation in terms of a typical or representative pattern in memory. For example, if a driver perceives a given roadway segment as familiar or very much like a familiar one, he or she may be caught off guard by a critical difference. In Michigan and Ohio, for instance, police typically pull vehicles over to the right berm or shoulder. It is less common to see stopped vehicles on the left shoulder or adjacent to a jersey barrier. Such 'surprises' may lead to crashes if other factors are also present (e.g., curve approach, adjacent traffic to prevent giving the stopped vehicle(s) wide berth, momentary glance from the road scene, etc.).

There is a paradox in schema-driven perception. Stimulus cues will be picked from the environment if either a) they are consistent with the expectations associated with the current situational understanding or b) if the cues are highly inconsistent with the current schema. This suggests that to break through to an inappropriate schema or expectation that a lead vehicle is moving, stimulus cues should be provided that are highly inconsistent with that expectation. Some evidence for this is provided below.

Prior Research on Cognitive Aspects of Police Car Conspicuity

This area of driver performance has received little research attention (Michael Sivak, personal communication, 2002). One very recent exception is the research into police vehicle conspicuity conducted by the Transport Research Laboratory (TRL) in England. A recent paper by Langham, Hole, Edwards, and O'Neil (2002) sheds light on cognitive factors that might contribute to stopped lead vehicle rear-end crashes, specifically crashes involving parked police vehicles. Two experiments were conducted using video recordings of drives toward parked police vehicles with lights on and conspicuity enhancements (e.g., retro reflective materials) present. Test participants viewed film clips and pressed a button as soon as they noticed a 'hazard' (self-determined by each test participant). Police vehicles were parked in a lane on a
four-lane undivided English roadway (two lanes in each direction). The police vehicle was parked either in 'echelon' orientation (at a 45-degree angle so that the vehicle side was visible to oncoming cars) or in 'in-line' orientation (i.e., the vehicle's long axis was parallel to the lane lines). Figure 1 depicts the two different orientations assuming a U.S. roadway.

![Figure 1. In-line and echelon parking.](image)

Results of the laboratory Experiment 1 indicated that the 'echelon' orientation was detected earlier than the 'in-line' orientation by experienced drivers. There was no difference in detection latency by inexperienced drivers as a function of police vehicle orientation. It was also reported (in laboratory Experiment 2) that the echelon orientation was detected earlier than the in-line orientation when the test participant was performing a working memory span task (highly cognitively demanding) while concurrently watching the film than when watching the film only. These results suggest an 'expectation' or 'false hypothesis' effect. Test participants expect an in-line police vehicle to be moving, while the 45-degree parking orientation provides a visual stimulus that helps reject this false hypothesis. (For inexperienced drivers, this latter point need not be true because inexperienced drivers have presumably not developed problem sensitivity of this kind). This false hypothesis might be implicated in the stopped lead vehicle rear-end crash phenomenon in general. People expect that in-line vehicles on an active roadway are moving because they usually are. A related hypothesis (not yet tested) is that a driver might detect an in-line vehicle, decide incorrectly (due to the false hypothesis) that it must be moving, and not visually sample it again until it is too late to avoid a collision. One caveat to mention is that the Langham, et al. experiments were conducted with police vehicles parked in a travel lane, not on a berm.

In terms of the schema explanation, the echelon parking method may be more indicative of a stopped lead vehicle because vehicles normally do not travel down the road at a crab-angle. When considering other types of cues that might indicate a police vehicle is NOT moving forward, looming should be considered as another powerful cue. The author recently observed a vanity item on a passenger car that might be adapted for this purpose. It was a fluorescent bulb
surrounding the license plate. The fluorescent bulb's gas would be released from the top and move laterally and symmetrically to surround the license plate completely. The effect was strikingly similar to a looming or visual expansion. Then the lamp would extinguish and the cycle would begin again. A similar treatment on a police vehicle, perhaps in the rear window or even around the outline of the entire vehicle itself (e.g., using electro chromic technology) could be quite effective… if the approaching driver is looking.

Wells (2002) also presented a looming display concept that may be a useful for conspicuity. As shown statically in Figure 2, the display concept consists of concentric rectangles of light that flash from inner rectangle to outer rectangle, pause, and then it cycles again. The impression is that of looming or expansion. One novel idea suggested by a Blue Ribbon Panel member is manipulating the lighting pattern to induce a directional arrow as well as provide looming. Looming display alternatives like those described here need to be refined and assessed for their effectiveness. They also need to be assessed for any unintended consequences that they may induce. One such unintended consequence might be a panic reaction from an approaching motorist who believes a vehicle is coming toward him or her and drives in an unsafe manner as a result.

Figure 2. Looming display concept (Source: Wells, 2002).

Langham and Rillie (2002) explain that humans are good at recognizing solid shapes and defined outlines but are poor at resolving partial outlines and outlines with no specific shape, especially if the outline is highly fragmented. (Breaking up the pattern of an object is one goal of camouflage). Once an object is seen and its shape has been determined, it is checked against a
mental representation in memory. They present a set of marking rules that are based on both physical and cognitive conspicuity considerations:

- Do not break up the outline of the vehicle or 'lose' parts of the vehicle outline or shape. Use a single color, with even the wheel trims marked.

- Show a color that drivers will detect easily in most lighting and contrast conditions. Langham and Rillie recommend retro-reflective orange for the entire vehicle color scheme.

- Ensure the marking of the vehicle is consistent, regardless of lighting conditions. Langham and Rillie caution that vehicles should not use one marking scheme in daylight and another scheme in darkness since this can compromise conspicuity in enhancements. They constructed a research vehicle with 3M Diamond Grade retro-reflective materials that provide color contrast while also being retro-reflective.

'Perceptual Tropism' or the "Moth Effect" Revisited. The term 'moth effect' is used for situations when people drive into the rear of lighted vehicles at night, presumably because they are drawn to the lights like a moth to a flame. Olson (1996) comments that when an intoxicated individual runs into the rear of a police car with all its lights going, this may not be an unreasonable assumption. Unfortunately, empirical research to support or refute this assumption is not cited or presented. However, people who are not intoxicated also run into stopped or slow-moving vehicles, to which investigators conclude that they must have failed to see it (through inattention or other mechanisms). Olson (1996) suggests that detection may not be the problem. In addition to seeing something, the driver must understand what it is, where it is, and what it is doing (e.g., in terms of motion). Olson suggests that it is the latter failing that may cause a driver to come upon another vehicle so as to be unable to avoid a collision (See Part 1 for a discussion of visual control of motion).

A study by Helander (1978) indicated that drivers sometimes steer toward an object of perception. Helander (1978) termed this phenomenon 'perceptual tropism.' Helander's on-road study was conducted in Sweden and involved 16 experienced drivers (more than 175,000 km driving during the 5 years preceding study participation) and 17 inexperienced drivers (less than 30,000 km of driving during the 5 years preceding study participation). Among other conditions, Helander measured the steering wheel angle, every 200 milliseconds, of each driver as the driver passed a car parked on the right side of the road. Measurements were obtained on both a curving road segment with limited sight distance and also on a straight highway segment with good visibility. Mean steering wheel angles were plotted from 10 seconds prior to 10 seconds after passing the parked car. Regardless of road type, the data revealed that the steering wheel was, on average, actually turned toward the parked car starting around 2 seconds prior to meeting or passing the other car. Maximum mean steering deflection was at the instant when the parked car passed. Helander interpreted this to reflect a directing of attention, looking, and motor response toward an object of perceptual significance. Though, he acknowledged that his study did not include measurements of lane position, Helander suggests that this perceptual tropism may be behind crashes where a stopped police vehicle is sometimes struck. For some people, apparently, highway patrol cars are so significant that they tend to drive into them. The author concludes that this research needed to be cross-validated for other traffic environments.
A subsequent study by Summala, Leino, and Viermaa (1981) extended the methodology of Helander (1978) and instead found support for a correction-maneuver explanation for the steering wheel angle data rather than perceptual tropism. According to this explanation, drivers actually steer away from the other vehicle prior to meeting it. However, steering dynamics dictate that the driver must also execute a corrective maneuver after the initial steering away maneuver in order to avoid departing the travel lane. (This makes intuitive sense if you think about how you change lanes. First you steer toward the destination lane, then about half-way through you put in a corrective steering input in the opposite direction such that your car is laterally positioned where you want it). This driving behavior does not necessarily result in the vehicle actually moving toward the other vehicle, though an over correction can result in real approaching. Helander (1978) measured only steering wheel angle while Summala et al. (1981) lane position of Finnish drivers on both narrow and wide 2-lane roads. The mean lane position at the instant of meeting an oncoming car on a narrow road was greater than that found for a similar meeting on a wide road. The steering wheel angle data of Helander for narrow roads showed a greater steering wheel deflection toward the approaching vehicle than a similar meeting on wide roads… a result consistent with the corrective-maneuver explanation. While Summala et al. (1981) point out that their study is not definitive, it lends plausibility to the corrective maneuver hypothesis.

**DUI-related Crashes.** Driving under the influence is identified as a contributing factor to rear-end crashes into stopped police vehicles (Kochhar and Tijerina, 2003). Alcohol, cannabis, ecstasy, amphetamines, cocaine, and LSD are substances that may affect driving safety. Of these, alcohol stands out as the most serious problem for driving under the influence. In the United States, drunk driving is a leading cause of traffic fatalities (National Traffic Highway Traffic Safety Administration, 2002).

Alcohol can have substantial effects on mood, judgment, perceptual-motor performance and cognitive performance. Generally, higher cognitive functions like dual-task timesharing degrade at lower doses of alcohol than some perceptual or motor abilities (Fleishman and Quaintance, 1984). In driving simulator and on-road studies, alcohol has been shown to induce the following effects as compared to non-intoxicated driving:

- Increased lanekeeping variability (Allen, Parseghian, and Stein, 1996);
- Induced tendency to restrict visual scanning of the road scene far ahead (Moskowitz, Ziedman, and Sharma, 1976);
- Increased speed variability or speed errors (Crancer, Dille, Delay, Wallace, and Haken, 1969)
- Increased reaction time latency to objects and events, e.g., road signs (Burns, Parkes, Burton, Smith, and Burch, 2002);
- Increased car following headway variability, especially when alcohol is combined with cannabis (Ramaekers, Lamers, Robbe, and O'Hanlon, 2000).
Perceptual, psychomotor, and cognitive effects are all present during intoxication (Evans, 1991). Beyond this, mood changes, altered judgment, and altered risk taking are also well known. The implications of intoxication for the effectiveness of countermeasures like echelon parking are unknown. This is an area in need of further research. Beyond this, enforcement of DUI laws remains a primary 'line of defense' against DUI-relate crashes in general, and rear-end crashes into stopped police vehicles in particular.

**Implications**

The area of cognitive conspicuity is a relatively new area of research as it applies to automotive safety in general and emergency vehicle safety in particular. What is known from cognitive psychology is that perception is selective, is initially stimulus-driven, and that it becomes concept or schema-driven. There are a number of cognitive decision biases that generally serve us well but that may occasionally have disastrous results. Paradoxically, a driver will pick up information if it a) is consistent with expectations or b) highly discrepant with expectations, i.e., of high 'surprisal' value.

The detection of a stopped emergency vehicle may not be enough for safe driving. The approaching driver must also perceive the vehicle's distance, location, and motion in order to make appropriate decisions about how to safely maneuver. Strong visual conspicuity cues can help and are usually sufficient to support safe driving. In the absence of strong visual cues, or in the presence of driver distraction, driver expectations fill in the gaps and intermittent checks of the driving scene are highly 'skeletonized'. Generally, these expectations serve the driver well, instilling a sense of confidence and safety because they have been correct (enough) so often. Occasionally, however, these expectations are in error.

The nature of the 'moth' effect is unclear and awaits further research. If real, this effect could also be interpreted as a cognitive error with heavy perceptual processing implications. What is clear is that, given insufficient time to recognize, decide, and act, the approaching driver risks running into a stopped vehicle under conditions when expectancies or schemas operate most freely. Rear-end crashes into stopped vehicles occurs most frequently under prototypical benign driving conditions (Knipling and Wang, 1993): daylight dry pavement, not necessarily heavy traffic density, on familiar roadways. Breaking through driver complacency is an important aspect of crash countermeasures generally.

The research methods needed to study cognitive conspicuity have not yet been fully developed (Langham and Rillie, 2002). However, what is known suggests the following points for further discussion and refinement into ideas suitable for evaluation:

- Drivers generally expect that vehicles ahead will be moving unless there is compelling and obvious evidence to the contrary (e.g., a noticeable traffic queue, a stop light on red, etc.).
- Cognitive conspicuity depends paradoxically on providing visual information consistent with expectations (that is picked up and evaluated most efficiently) and
on providing information that is NOT consistent with a complacent expectation that all is normal. Emergency flashers, flares, and warning triangles (Lyles, 1980; Lum, 1979) are part of the technology to break through such expectations and alert the driver to hazards ahead. To the extent that these are known as hazard indicators, they will be effective in most instances. Occasionally, even the emergency warnings will not be enough.

- There is a need to identify more salient means to break through an erroneous expectation. The research of Langham, Hole, Edwards, and O'Neil (2002) suggests that vehicle orientation in a parked state may be one means to achieve this end. The superiority of echelon parking (as compared with in-line parking) may arise from the fact that vehicles generally cannot move down the roadway at such a crab-angle. This would, then, violate an assumption that the emergency vehicle is in 'hot pursuit.'

- Other types of cues that break an expectation that vehicles ahead are moving in the same direction as the approaching vehicle might take advantage of certain perceptual illusions that break the expectation in a specific way. For example, a display on a parked vehicle that 'looms' (see Part 1 on visual control of motion) would be one example of how a parked vehicle could be made to appear moving in an unexpected direction. Of course, any such countermeasures needs to be assessed against the possible risk of inducing a strong reaction on the part of the approaching driver that causes the individual to lose control of the vehicle. Driver loss of control upon sighting a police vehicle has been a cause of a number of rear-end crashes into those vehicles.

- The presence of a pedestrian on the roadway or side of the road is sufficiently unexpected that it breaks through driver expectations to the contrary. In the UK, for example, highly visible retro-reflective vests have been issued to police officers for conspicuity enhancements. The benefits of this effect would have to be weighed against the possibility of other types of harm coming to the vest's wearer, e.g., being shot at by a sniper while standing on the road.

The area of cognitive conspicuity will likely interact with visual control of motion and lighting and markings. That is, countermeasures to false expectations or schemas will, in all likelihood, take the form of visual stimuli, or else will involve direct and unambiguous communications to the approaching vehicle by messages transmitted directly to the vehicle interior or other means.

The area of drunk driving crash countermeasures merits further research. It is not clear to what extent countermeasures like echelon parking can be effective with an intoxicated driver. One potentially valuable study would be to replicate the Langham et al. (2002) research with intoxicated drivers to determine if similar gains over in-line parking are found. The altered cognition brought about by intoxication may be sufficiently great that crash countermeasures are largely ineffective. Enforcement of drunk driving laws will then be the primary, if not only, means to reduce the risk of such crashes.
References


Part IV:  
Recommendations: Crash countermeasures and Research Needs

The following recommendations range from the general to the specific. The general recommendations are likely to enhance highway safety in multiple ways. The specific recommendations are, on the other hand, targeted to police vehicles. Always, the feasibility of specific recommendations must be assessed in terms of practicality, costs, benefits, and other priorities.

General Recommendations

1. **Provide sufficient sight distance to oncoming motorists given prevailing driving conditions.** When stopping, police officers should consider the sight distance available to oncoming motorists. It is also appropriate to provide an extra margin of safety for slick roads, nighttime driving conditions, and the like. Insufficient sight distance might arise if the police vehicle is stopped, for example, on the far side of a curve or behind a hillcrest. In such cases, the oncoming driver may brake or steer in a startle response and lose control of the vehicle.

2. **Avoid stopping in 'unexpected' areas.** Motorists depend greatly on expectations while driving. Unexpected events are potentially dangerous and should be avoided to the extent possible. For example, the crash problem description for this effort identified that stops on the left-hand shoulder are disproportionately represented in the reviewed crash records as compared to stops on the right-hand shoulder. One reason for this may be related to driver expectations.

3. **Maintain roadway lane lines and edge lines, especially important for night driving.** Night driving can be more difficult than daytime driving. Lane lines and other pavement markings provide texture cues to distance and demarcate a path for the driver to track while driving under darkness. A plausible hypothesis (suitable for empirical test) is that degraded or absent lane lines can contribute to road departure crashes in general. In particular, there may be a link between poor-visibility pavement markings and some rear-end crashes into police vehicles stopped on the shoulder.

4. **Avoid stopping in areas where there is high likelihood that drivers will not be looking for you.** The crash review uncovered instances of stopped police vehicles that were rear-ended while stopped along an on-ramp. Given that drivers entering the limited-access highway will often be looking to the left mirror or over-the-shoulder, there is an increased chance of collision.
Recommendations on Lighting Systems, Vehicle Markings, High Visibility Vests, and Flares

1. Emergency Lighting Systems are characterized by their light sources, light output, light color, and flash rates:
   - Luminaire Type: No specific recommendations for light sources (e.g., halogen, strobe, LED) are offered at this point.
   - Light Output: Compare alternative lighting systems by inspection for their perceived brightness or 'flash energy' as determined by Bloch's Law rather than rely on candlepower ratings alone;
   - Light Color: To promote conspicuity in various day and night viewing conditions, multi-color lighting is recommended. For example, the common red-blue combination of lights may be augmented by amber lights sequenced to generate an arrow to direct traffic around the stopped emergency vehicle. Multicolor lighting systems are recommended based on the following considerations:
     - Amber lenses pass greater light than red or blue lenses and so can be quite visible. Amber generally means 'yield.' However, amber lights might be less visible under certain daylight conditions and can be glaring under nighttime viewing conditions.
     - Red lights signal 'stop' and are more readily detected in daylight than blue lights. However, they may sometimes be confused with red tail lights in surrounding traffic. Red lights can be masked somewhat at dusk by a red sky, and can induce a moving-away-from-you illusion when viewed in darkness even though the lights are stationary.
     - Blue lights are more visible than red lights in dark viewing conditions and may be less glaring than amber lights at night. But, blue lights are not reliable indicators of motion or lack of motion at night. To promote conspicuity in various day and night viewing conditions, multi-color lighting is recommended. For example, the common red-blue combination of lights may be augmented by amber lights sequenced to generate an arrow to direct traffic around the stopped emergency vehicle.
     - It should be noted that some authorities have expressed concern that complex (in number, color, or both) emergency lighting is potentially confusing. A field comparison of different lighting systems' complexity would be helpful in empirically resolving this issue.
   - Flashing lights and Flash Rates: Flashing lights are more easily detected in the visual periphery than a constantly glowing light. A rotating beacon can be more conspicuous than a flashing (ON-OFF) light. Use flash rates slower than the 6 to 40 flashes per second range (i.e., slower than 360 flashes per minute) to minimize the possibility of triggering epilepsy in susceptible persons. Higher flash rates (4 Hz or 240 flashes per minute) signal greater urgency than slower flash rates (1 Hz or 60 flashes per minute) but are also more annoying. Multiple beacons (e.g., 4 beacons) are rated as more attention getting than single beacons.
2. **Markings:** At present there is a need for field data to determine the effectiveness of various markings. However, theory and inspection suggest that the following may be useful in enhancement of emergency vehicle conspicuity:

   - Avoid markings or color schemes (e.g., Battenburg livery patterns) that break up the contours of the vehicle and so may actually act as camouflage;
   - Consider rear-end chevron patterns that consist of high-contrast colors and convey the impression of a barrier;
   - Consider markings that demarcate or outline the body of the vehicle.

3. **High visibility vests or outer wear** may increase pedestrian officer conspicuity and so alert the approaching motorist to exercise extra caution. However, this must be weighed against other safety and security concerns such as restricted access to equipment or the risk of being fired upon.

4. Some authorities stress the importance of flares as indicators of an emergency or presence of stopped vehicles. Other authorities claim that the flares are a potential distraction in their own right. Evidence for the latter was not found in the reviewed literature while operational experience suggests benefits to flares.

**Concepts for Research and Development**

1. It has been pointed out that looming is a powerful cue to braking behavior. A looming display might, therefore, provide a crash countermeasure if developed and deployed effectively. Part III, on lighting and conspicuity, presents a figure showing an example of a looming display that consists of concentric rectangles of light that flash from inner rectangle to outer rectangle, pause, then cycle again. Another concept for a looming display makes use of an array of lights around the edge of the police vehicle's rear window. By appropriately sequencing the onset, duration, and intensity over time of the lighting from top-center of the rear window and moving out laterally toward the bottom center, a looming effect may be achieved. The effectiveness of these concepts, and others, merits an experimental investigation for feasibility. If such concepts have promise, a field study may be appropriate to estimate their real-world effectiveness. Equally important, such research should also be directed toward the assessment of potential unintended consequences, e.g., panic reaction from approaching motorists.

2. There is a need to compare vehicle color, rear-end chevron patterns, and other markings and color treatments to ascertain safety impacts.

3. There is a need to identify more salient means to break through an erroneous expectation. The research of Langham, Hole, Edwards, and O'Neil (2002) suggests that vehicle
orientation in a parked state may be one means to achieve this end. The superiority of echelon parking (as compared with in-line parking) may arise from the fact that vehicles generally cannot move down the roadway at such a crab-angle. This would, then, violate an assumption that the emergency vehicle is in 'hot pursuit.'

4. The efficacy of echelon parking, looming displays, lighting systems, or other conspicuity measures (markings, flares, high-visibility vests or outerwear) should be evaluated for effectiveness with intoxicated persons to determine what impact, if any, such countermeasures may have on them.

5. The effects on the drowsy, distracted, or intoxicated driver of different methods of conspicuity enhancement require further research.

6. While not part of visual conspicuity, nevertheless in-vehicle auditory or visual warnings might be presented to the driver upon approach to a stopped police vehicle. Such warnings might indicate "crash ahead", lane blocked ahead", "stopped police vehicle ahead", and so forth. In-vehicle warning systems have been studied by the US Department of Transportation as part of a its In-Vehicle Signing and Warning Systems (IVSAWS) research (Shirkey, Mayhew, and Casella, 1996). Such technologies have been developed in Europe as well (though not specifically for police-vehicle rear-end crash problem mitigation).

Concluding Remarks

There are many questions for which more research is needed (or has already been done and needs to be uncovered). The research generally takes the form of comparisons between different 'treatments', i.e., lighting systems, vehicle color or markings, road treatments, vehicle parking orientation, and so forth. The intent is to determine what 'works' and this generally takes the form of a two-step research agenda, beginning with an experiment, then followed by a field study. Some examples will clarify this approach.

Consider the effectiveness of echelon parking to increase conspicuity to intoxicated drivers. An experiment might be conducted similar to the one reported in Part III of this report. Random assignment, administration of careful doses of alcohol, inclusion of placebo and no-drink control groups, and other procedures would be employed to ascertain if echelon parking is associated with any different detection rate or latency as compared to in-line parking. The experiment would control for many factors and employ a limited sample of test participants. The experiment is, in effect, a kind of feasibility study.

Suppose that the results turn out favorably for echelon parking. The next question is, 'Does it work in the real world?' Here, the observational before-after study as discussed by Hauer (1998) becomes very important. As Hauer points out, safety changes over time for many reasons. Because of this, it is critically important to design such a field study with appropriate comparison groups, with corrections for changes in conditions, with care for base rates of
occurrence to be factored in, with sufficient numbers of participants and sufficient time to gather statistically reliable and sensitive data, and so forth. An observational field study provides a 'confirmation study' of the impact of a crash countermeasure on safety. Careful design of both experiments and field studies will both be necessary to uncover the answer to the question as: "Do 'treated' police vehicles get struck less often than 'untreated' police vehicles?"

It may sometimes be the case that from real-world experience 'the research has already been done.' That is, existing safety records might answer relevant questions about conspicuity and safety if appropriately analyzed. Take vehicle color and crash involvement as an example. Safety records might be examined and analyzed to determine the relationship of vehicle color (perhaps established through Vehicle Identification Number or VIN) and crash involvement. If suitable databases can be found, striking versus struck vehicles involved in rear-end collisions might be sorted out as a first pass. Then, other mitigating factors would be identified and statistically factored out such as base rates of occurrence of vehicles of different colors, makes, and models; exposure in terms of miles driven and road types traveled on; driver age and experience; seasonal variations in driving conditions; and so on. It may then be possible to calculate hazard exposure in a relative sense based on vehicle color. The analysis of happenstance data not experimentally gathered, is always quite complex. But actual field experience is the ultimate arbiter of what matters and what does not.

References

