Application of human factor centered checks in Road Safety Audits of highway design projects in Spain

José M. Pardillo Mayora
Technical University of Madrid (UPM)
ETSI Caminos, Canales y Puertos
C/ Profesor Aranguren s/n
28040 Madrid (Spain)
Phone: (+34) 913366652
Fax: (+34) 913366654
e-mail: jmpardillo@caminos.upm.es

Rafael Jurado Piña
Technical University of Madrid (UPM)
ETSI Caminos, Canales y Puertos
C/ Profesor Aranguren s/n
28040 Madrid (Spain)
Phone: (+34) 913366750
Fax: (+34) 913366654
e-mail: rjurado@caminos.upm.es

Revised from the original submission for presentation at the 4th International Symposium on Highway Geometric Design, June 2010

Word count:4 404 < 7,500 Submission date:10/03/10

ABSTRACT

A Road Safety Audit is a formal and independent review of a highway design project by an experienced team of safety specialists, addressing the safety of all road users. During the audit process, a team of qualified, independent experts identifies potential safety risks in the design, assesses the safety performance of the projected highway, and proposes recommendations for improvement. Road safety audits provide an opportunity to consider human centered design and usability concepts that are not explicitly contemplated in the traditional road design process. In Spain, the Road Administrations have initiated the process to incorporate Safety Audits to the highway design process. This paper presents the results of a research effort conducted at Madrid Technical University and funded by the Spanish Ministry of Infrastructure to develop a methodology and reference materials for the application of RSA in Spain. User centered design principles were reviewed and synthesized to characterize user needs and constraints in relation with the configuration of the road. As a result, human factors related design checks were proposed for application in the Road Safety Audit process with a focus on accounting for the needs and constraints of the human operator to achieve the safest operational conditions for the system user/vehicle/road/environment. Conclusions were also obtained on the orientation of future research required to develop quantitative highway design criteria based on driver's perception and workload.

Key words: Highway design, road safety, audits, ergonomics, user centered design, usability

BACKGROUND

A road safety audit (RSA) is a formal and independent review of a highway design project by an experienced team of safety specialists, addressing the safety of all road users. During the audit process, the independent safety experts identify potential risks in the design, assess the safety performance of the projected highway, and propose recommendations for improvement.

The RSA process was initially applied in the United Kingdom during the late 1980's. In 1990 the Design Standard HD 19/90 and Advice note HA 42/90 were introduced by the UK Department of Transport as part of the Design Manual for Roads and Bridges. This made safety audit mandatory on trunk roads and motorways schemes from 1991 onwards (1, 2, 3).

Since then, RSA have spread internationally. The RSA was introduced in Australia and New Zealand at the beginning of the 1990's. In 1994, Austroads published a Manual to serve as a guide for the audit process of main highways as well as local roads (4).

In Europe, the highway administrations of Denmark, Norway, Iceland and Ireland have made safety audits an integrating part of their highway design process. Other countries such as Germany, France, Portugal, Italy, the US and Canada have developed RSA manuals or guidelines adapted to their local conditions, and have started implementing audits. In Canada and the US several provinces and States have also conducted pilot applications of the process (5).

All of these countries have developed reference materials for carrying out the audits. However, national methodologies cannot be exported without adjusting it to the local characteristics of each country, as there are important differences as regards the behavior and culture of the drivers and other road users, the technical specifications and the configuration of their road networks, and to a lesser degree, the vehicles.

In Spain, the National Road Administration has initiated the process to introduce Safety Audits at the highway design stages. Researchers at the Technical University of Madrid (UPM) collaborated with the Ministry of Infrastructure to develop a methodology and reference materials for the application of RSA. User centered design concepts were considered to identify road user needs and constraints in relation with the configuration of the road. As a result, basic criteria related to the human factors were derived an applied in the development of check lists for the application of RSA in Spain (6).

USER CENTERED DESIGN

Traffic safety depends on the adequate operation of the system constituted by the road users, the vehicles and the highway environment. In most traffic accidents, human error is a determining factor. Better understanding of road users behavior and its relation with infrastructure characteristics is required to avoid infrastructure configurations that contribute to these errors.

The user centered design approach is already being applied by the automotive industry as a key element in the development of human-machine interfaces of Advanced Driver Assistance Systems (7). User needs and constraints are the primary focus in a user centered design process. The designer should aim at making the product/system easy to use and to understand. A user centered design process urges the designer to consider human operator needs, interests and prerequisites throughout the design process. Along these lines, highway design should aim at facilitating the drivers' task and at inducing safe driving patterns.

PSYCHOLOGICAL FACTORS IN DRIVING

The fact that some drivers suffer accidents under the same circumstances that many other drivers have gone through without any harm, have given rise to investigation regarding the variables that may influence human behavior during driving in order to study whether it is possible to reduce the frequency of these accidents. These variables can be classified into three groups: the physical driving capacity (aptitude), the necessary knowledge (training and experience), and the driver's psychological condition (attitude).

Keskinen (8), building on previous work by Michon (9) described three hierarchical levels in the factors influencing driver's behaviour:

1. Vehicle maneuvering. The lowest level refers to vehicle control such as shifting gears or steering maneuvers. Evasive maneuvers, control in different weather conditions, and use of passive safety measures such as seatbelts are also included in this level.
2. Mastering of traffic situations: adaptation to specific traffic situations, such as overtaking, speed choice, and perception of hazards are included in this level.
3. Goals and context of driving: This level focuses on the context in which driving is performed, particularly on the planning of trips, and the choice of travel-mode, time of day, road situations or driving circumstances, including driving under influence of deteriorating conditions or substances.

Hattaka et al. (10) added a fourth level, encompassing personal motives and beliefs assuming that that lifestyle, social background, gender, age, income etc. has an influence on driving behaviour and attitudes towards driving. This level refers to personal motives and tendencies in a broader perspective than simply conducting the driving task.

This hierarchical approach assumes that abilities and preconditions on a higher level influence the demands and preconditions on lower levels. Additionally, there are aspects of driving or traffic that can increase the risk, such as perception of the traffic situation, speed adjustment, and risk acceptance.

Risk perception and acceptance

The risk associated with a human activity may be defined as the degree of exposure of the person who undertakes an activity to suffer damage or potential losses.

There are two concepts of traffic related risk:

- The objective risk is the actual risk of an accident occurring at a given site in the network. It is possible to measure it, if sufficient statistical information is available.
- The subjective risk is the risk that is perceived by the road user. Users judge risk through the stimuli that they receive when they are on the road.

Subjective risk is an important factor that determines the driver's behavior. It is related to the objective risk because the users base their perceptions on the physical characteristics of the environment, and learn through experience and common sense which situations and places are objectively dangerous. However, perceptions do not always truthfully correspond to reality, and a lack of perception of the real risk level is often the reason for an accident (11).

Traditionally, it has been considered that accidents that take place on a certain road section are independent from the characteristics of the remaining road network. Some psychologists who believe that the driver adjusts his conduct to the changes that take place in the environment have questioned this model. When he perceives a change in the risk level at a certain point of the journey, the driver will change his conduct and try to compensate the risk variation. When it increases, the driver feels threatened and compensates by reducing the speed and acting with more caution, which influences on the functioning of the later sections from the safety point of view. There is a theory that holds that the compensation of risks is homeostatic (from the Greek words *homeo*: concurrent or similar, and *stasis*: condition or state of the things), so that the drivers have a pre-established risk level per time unit on the road, and adapt their behavior according to the changes in the risk that they perceive in order to reach the established level. Consequently, if the subjective risk level is less than the acceptable level, people tend to start doing actions that increase their risk exposure. However, if the subjective risk level is greater than the acceptable level, then greater precautions are taken (12). Although it is generally accepted that risk compensation exists up to a certain point, it has not been proven that it is homeostatic. Smiley asserts that intelligent reallocation of attention and effort is possible and, therefore, there is no expectation that behavioral adaptation will result in constant crash rates (13).

The risk associated with a certain highway element can be evaluated differently by different drivers or even by the same driver at different times. Furthermore, the perceived risk can be substantially different from the objective risk for any user/place interaction so that the accidents occur more frequently when the perceived risk underestimates the actual risk. It can be concluded that the traffic safety level diminishes if the objective risk is higher than the perceived risk. In this respect, safety improvement measures may take two forms:

a) To increase the perceived risk through sign-posting or other means that attract the attention of the user toward risk factors that are unperceivable or difficult to perceive.

b) To reduce the objective risk.

The measures will be effective if the balance between perceived and objective risk is adequate.

Mental work load

The driver's mental workload measures the intensity of the mental activity that the driver has to carry out during the driving process. It is defined as the quantity of information that the driver must process per time unit. The concept is based on the assumption that the act of responding to stimuli takes a finite amount of effort and that the total amount of effort an individual can expend is limited.

The workload that can be handled before performance begins to deteriorate defines maximum capacity for a particular individual. The allowable mental workload sets the limit for the information processing and vehicle control tasks that can be imposed on an operator; thus, an estimate of workload facilitates good system design (14).

The mental load increases if the complexity of the highway design is high. It also increases if the time available for processing the information is reduced due to the speed of the traffic or reduced visibility. An excessive workload results in poor driving performance as it prevents the driver from making the correct decisions.

On the other hand, an excessively low workload also induces low driving performance as it favors lack of attention and distractions. The absence of visual variation due to fog, darkness or very long, monotonous access sections produces a reduction of the workload and the attention. The monotony of the highway environment produces a reduction in the attention, which the user tends to compensate by increasing the speed (15).

In highway design, it is important to avoid situations in which the driver experiences a work load due to information processing or decisions that are insufficient or excessive. A medium load favors the best driving quality with least errors.

In order to estimate the mental load of a highway element, Messer et al. developed a method that assigns a mental workload index to each highway element. The index values on a scale from 0 to 6 were established based on subjective evaluations by a group of experts. A value of 0 corresponds to elements that do not pose any problem, and a value of 6 is given to elements presenting a serious problem to the driver. The value of this index is modified for each particular case by applying correction factors that depend on the visibility of the element, the degree of the drivers' familiarity with it, the likeliness that it will occur in the specific itinerary, and the mental load caused by the contiguous highway elements (16).

Further research is required to develop tools that allow estimating workload from highway design characteristics. Until these are available, the assessment has to rely on the expert judgment of road safety auditors.

With the aim of limiting the mental workload for the drivers, Kraemer et. al. (17) proposed a set of minimum perception and reaction time requirements for a safe design of critical highway elements that vary from at least 3 s prior to a curve to 10 s at complex interchange merge zones.

VISUAL PERCEPTION

Driving an automobile involves an information handling process, which can be divided into three phases:

1) The information that is required in order to drive the vehicle is extracted from the highway and its environment, the vehicle sensors, and the driver's dynamic sensations.

2) This information is processed.

3) The driver operates the controls of the vehicle accordingly (uses the steering wheel to change the direction and the accelerator or the brakes to modify the speed).

The greater part of the information that is required to perform the driving process is visual. Although it is not possible to identify and describe all the factors that influence the visual perception, Lunefeld and Alexander proposed the following conditions (18):

- In order for the information to be perceived, it must be visible and attract driver's attention. The signing and marking elements used to convey the information must be properly located and have adequate physical characteristics (size, form, contrast, and color).
- Visual information should be located inside the driver's visual field and its clear viewing cone for the anticipated traffic speed.

Glare caused by direct sunlight can produce substantial reduction in drivers´ vision performance. Visual impairment caused by glare is a physiological effect caused by the light scattered within the eye onto the retina reducing the contrast of the retinal image. Sun glare may impair driver's vision at critical situations compromising safety. A methodology to determine the days and times of the year when sun glare may impair drivers' vision on a particular road section depending on its geographical location, the geometric design of the road, and the physical characteristics of its environment was developed at the Technical University of Madrid (19). Based on this methodology a software tool was developed to support the analysis of driver vision impairment problems originated by sun glare and to facilitate the design of countermeasures to prevent potential safety hazards caused by these situations taking into account the geometric design of the road and the shielding effect of roadside elements like tree screens.

On the other hand, perception is more limited and slower in the dark. In the design process, it is important to consider how to avoid perception deficiencies at night.

ROAD DESIGN AND DRIVER EXPECTATIONS

Drivers adjust their driving patterns to their perception of the characteristics of the road there are traveling on. This perception is influenced firstly by the immediate experience obtained from the road sections that the driver has just driven through, but it depends also on the accumulated experience from previous trips, as to the elements that are usually encountered on similar itineraries. This creates some expectations on the part of the driver as to what he is going to find. When he finds himself in an unexpected situation, he must make a decision and act quickly, which increases the risk of making an error. In certain cases, these errors cause the loss of control of the vehicle and consequently a possible accident.

Geometric design consistency

Geometric design consistency is the conformance of geometry of a highway with driver expectancy. Sudden speed reductions that are made necessary by the presence of a sharp curve can surprise drivers and increase the risk of errors. Research in Spain by Pardillo and Llamas (20) showed that the design speed reduction from adjacent segments is significantly correlated with accident rates.

Several measures of design consistency have been identified in the literature and models have been developed to estimate these measures. Castro, Pardillo and Sánchez (21) assessed the relationship between alignment indices and accident records, and the applicability of these indices to roadway design consistency evaluation for two-lane rural highways. Ten alignment indices were considered, and its relation with crash rates over a 5 year period was analyzed. Based on the results of the analysis, the most suitable indices to evaluate roadway design consistency were identified. Additionally, threshold values of the selected indices for consistency rating of roadway segments were established.

Highway legibility and speed choice

The term highway legibility refers to the ability of the road users to establish an accurate and easily understandable image of the highway characteristics, the driving patterns that are expected of them (speed, priority, etc.), and of the probable or possible movements by the other users (22). It results from the adequate combination of the geometric design, the signing and delineation, the roadside design, and the treatment of the highway adjacent areas.

Drivers' speed choice is influenced by perceptual cues from the highway design and its environment. Highway legibility is thus very important to afford drivers with the right cues for a safe speed choice.

Another aspect of speed choice is speed adaptation between two connecting highway segments. Prior to deciding on the design of a highway section, the geometric characteristics of the adjacent sections, its signing and marking criteria, intersection types and any other features that may have a relevant influence on drivers perception should be studied in order to determine the measures that are necessary to ensure a gradual and easily recognizable transition ensuring that there will not be situations where the driver's expectations may be deceived.

In particular, the variations in the characteristics of the cross section have an important influence on safety. The most important aspects are the lane width, width and condition of shoulders, and on dual-highways, the width and state of the median. The changes in any of them must be gradual and be appropriately signed.

HUMAN FACTOR BASED CHECKS FOR ROAD SAFETY AUDITS

Based on the previous findings, the following checks related to the human factors were recommended for use in the implementation of RSA in Spain (23):

1) Related to driver's perception of hazards

- Check the coherence of the horizontal and vertical alignment parameters and the anticipated operation speeds.
- Check the design to identify situations in which perceived risk is likely to be lower than objective risk and recommend either changing the design to reduce the objective risk or increasing the perceived risk using adequate signing and delineation.
- Analyze the probability of occurrence of traffic congestion situations at locations with reduced sight distance affording less that 6 s perception and reaction time at the estimated operating speeds. If so consider the necessity of installing queue detectors and variable message warning systems.

2) Related to driver's workload

- Check that the placements of signs be chosen according to the importance of information, and avoid information be presented to the driver when and where it is not essential.
- Check that the information be presented sequentially for each of the control, guidance, and navigation task.
- Check that the available sight distance at critical design elements (entry and exit ramps, intersections, cross section changes, pedestrian crossings, merging sections) affords a sufficient perception and reaction time to the driver at the anticipated operation speeds taking into account the driving environment complexity.
- Check the separation between design elements that may cause high driver's workload (complex guide signs, merging lanes, diverging lanes, lane drops, potential pedestrian crossing sections, tight alignment elements, etc.).

3) Related to driver's visual perception

- Check that the visual information required for safe driving be located inside the driver's visual field and its clear viewing cone for the anticipated operation speed.

- Check the conspicuity of critical signing elements: stop signs, speed limits, no-passing signs, etc. If necessary consider recommending providing the same information by using both signs and pavement markings.
- Check for the eventual occurrence of glare at critical sections: tunnel exits, freeway entrance or exit ramps, tunnel exit segments or at intersections. If necessary consider recommending changes in alignment or the adoption of countermeasures like tree screens, overhead shields, etc.
- Check for situations in which perception deficiencies may occur at night. If necessary recommend the installation of adequate delineation devices or lighting.

4) Related to driver's expectations

- Check the homogeneity of design parameters with those of highways with equivalent functions within the highway network to ensure that users can anticipate the characteristics of the road they are driving along, and adjust their behavior.
- Check the coherence of design criteria and operational conditions: speeds, access control, etc.
- Check geometric design consistency using the thresholds in alignment indices. If necessary recommend changes in alignment.
- Identify variations in the characteristics of the cross section: lane width, shoulder width and condition and check that the changes in any of them be gradual and appropriately signed.
- Analyze the geometric characteristics of adjacent sections to that under review, its signing and marking patterns, intersection layout and any other features that may have a relevant influence on drivers and check the homogeneity.

CONCLUSIONS

The following conclusions can be drawn from the results presented in this paper:

- Road safety audits provide an opportunity to consider human centered design and usability concepts that are not contemplated in the traditional road design process.
- Highway usability is related to the ways in which the highway system is used in a specific culture. Culture is a broad concept that not only includes ethnical culture but also gender, age, social status, education, etc. All these factors influence on the users' behavior, and it is therefore important to take them into consideration in the design process.
- The main focus of highway design should be achieving the safest operational conditions for the system user/vehicle/road/environment, taking into account the needs and constraints of the human operator.
- Further research is required to develop tools to quantify driver's perception quality, highway legibility, subjective risk, and workload in relation with highway design. Until these are available, the assessment has to rely on the expert judgment of road safety auditors.

REFERENCES

1. Department for Transport. *Design Manual for Roads and Bridges Volume 5 Section 2 Part 2 HD19/03 Road Safety Audit.* London, 1991.
2. The Institution of Highways and Transportation. *Guidelines for Road Safety Audit.* London, 1996.
3. Highways Agency. *Standard for Road Safety Audits HD19/03*. Department for Transport. London, 2003.
4. AUSTROADS. *Road Safety Audit 2nd edition*. Sydney, Australia, 2002.
5. Wilson, E. and Lipinski, M. *NCHRP Synthesis of Highway Practice 336: Road Safety Audits*. Transportation Research Board, National Research Council, Washington, D.C., 2004.
6. Pardillo Mayora, J. *Development of a Methodology for the Application of Road Safety Audits* (in Spanish). Fundación Agustin de Betancourt, Madrid, Spain, 2004.
7. Yang, C. and Flicker, J. Using Human Information Processing Principles to Design Advanced Traveler Information Systems. In *Transportation Research Record: Journal of the Transportation Research Board, No.1759*. TRB, National Research Council, Washington, D.C., 2001.
8. Keskinen, E.. *Why do young drivers have more accidents?* Junge Fahrer Und Fahrerinnen. Referate der Esten Interdiziplinären Fachkonferenz. Berichte der Bundesanstalt fur Strassenwesen. Mensch und Sicherheit, Heft M 52, Köln, Germany, 1996.
9. Michon, J. A. Explanatory Pitfalls and Rule-Based Driver Models. Accident Analysis and Prevention, Vol 21, pp. 341-353.
10. Hattaka, M. et al. *Results of EU- Project GADGET, WP3*, European Commission, Brussels, 1999.
11. Wright, C. and Boyle, A. *Road Accident Causation and Engineering Treatment: A Review of Some Current Issues*. Traffic Engineering and Control, 1987.
12. Wilde, G. J. S. The Theory of Risk-Homeostasis: Implications for Safety and Health. *Risk Analysis, Vol. 2* pp. 209–255, 1982.
13. Smiley, A. Behavioral Adaptation, Safety, and Intelligent Transportation Systems. In *Transportation Research Record: Journal of the Transportation Research Board, No.1724*. TRB, National Research Council, Washington, D.C., 2000
14. Zeitlin, L: Micromodel for Objective Estimation of Driver Mental Workload from Task Data. In *Transportation Research Record: Journal of the Transportation Research Board, No.1631*, pp. TRB, National Research Council, Washington, D.C., 1998.
15. PIARC. *Committee 13- Road Safety Report*. Proceedings of the XXIInd Road World Congress, Durban, 2003.
16. Messer, C. et al. *Highway Geometric Design Consistency Related to Driver Expectancy* RD-81/036, Federal Highway Administration, Washington D.C., 1981.
17. Kraemer, C. et al. "*Ingeniería de carreteras*". McGraw Hill, Madrid, 2003.
18. Lunefeld, H. and Alexander, G. *A User´s Guide to Positive Guidance*. Federal Highway Administration. Washington DC, 1990.

19. Jurado-Piña, R. and Pardillo-Mayora, J.M. "*A methodology to predict driver vision impairment situations caused by sun glare*." Transportation Research Record Journal of the Transportation Research Board 2120 12-17, Washington DC, 2009.
20. Pardillo-Mayora, J.M. and Llamas, R.: "*Relevant Variables for Crash Rate Prediction in Spain's Two Lane Rural Roads"*. Presented at the Transportation Research Board 82nd Annual Meeting, Washington D.C., 2003.
21. Castro, M. ; Pardillo-Mayora, J.M.. and Sanchez, J. F.: *Alignment Indices as a Tool to Evaluate Safety and Design Consistency in Two Lane Rural Roads*.3rd International Symposium on Highway Geometric Design Compendium of Papers CD-ROM. Transportation Research Board, Chicago, Il, 2005.
22. Brenac, T. et al: *Sécurité des routes et des rues*. Centre d'Études des Transports Urbains (CETUR) & Service d'Études Techniques des Routes et Autoroutes (SETRA), Bagneux, France, 1992.
23. Pardillo-Mayora, J. *Estudio de criterios de auditorías de seguridad vial basados en la relación de las características de las carreteras y el proceso de conducción.* Fundación Agustin de Betancourt, Madrid, Spain, 2006.