



# **Misestimating time of collision in the tunnel entrance due to a disturbed adaptation**

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bedingt durch eine gestörte Adaptation**

**Estimation incorrecte du temps de collision à l'accès d'un  
tunnel due à une adaptation perturbé**

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**Forschungsprojekt FGU 2010/003 auf Antrag der  
Arbeitsgruppe Tunnelforschung (AGT)**

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## Zusammenfassung

Der Sonnenstand ist ein Risikofaktor! Dies folgt aus einer statistischen Analyse von Verkehrsunfällen, die sich in der Nähe der beiden Portale des Gubristtunnels ereignet haben. Auf die Portale des Gubristtunnels zufahrende Autofahrer und Autofahrerinnen sind einem erhöhten Unfallrisiko ausgesetzt, wenn sie die Sonne knapp über der Portalwand sehen können. Ebenso ist für diese Autofahrerinnen und Autofahrer das Unfallrisiko erhöht, wenn sie durch Spiegelreflexion des Sonnenlichtes an der Portalwand geblendet werden können. Um das Unfallrisiko möglichst gering zu halten, sollten der Sonnengang, Reflexionseigenschaften, Orientierung und Form der Portalwand bei der Planung berücksichtigt werden. Bauliche Massnahmen zur Abschattung der Sonne können ebenfalls berücksichtigt werden. Im Falle des Gubristtunnels wären diese mit hohem Aufwand verbunden.

Um den Beitrag der Blendung am oben genannten Unfallrisiko zu untersuchen, wurden vier Laborexperimente durchgeführt. Die Experimente wurden so konzipiert, dass sie vor allem Erkenntnisse zu den bei Portalen häufig auftretenden Auffahrunfällen liefern sollen.

Ein erstes, in unserem Fahrsimulator durchgeführtes Experiment, zeigte überraschenderweise, dass eine starke ( $28'720 \text{ cd/m}^2$ ), in der Nähe des Blickes gerade aus ( $28^\circ$  im peripheren Gesichtsfeld) montierte Blendquelle, nicht notwendigerweise die Fähigkeit mindert, die Geschwindigkeit eines voranfahrenden Fahrzeuges richtig einzuschätzen. Die Resultate des Experimentes lassen vermuten, dass nebst der Blendung, auch andere Faktoren zum Unfallrisiko beitragen, wie z. B., die beim Tunneleintritt sich schnell ändernden Inhalte der visuellen Umgebung.

In einem zweiten Experiment wurde untersucht, wie sich der schnell ändernde Inhalt einer visuellen Umgebung auf das Vermögen Geschwindigkeiten zu schätzen, auswirkt. Die Resultate des zweiten Experimentes zeigen, dass die Schätzung der Geschwindigkeit eines voranfahrenden Fahrzeuges ungenauer wird, wenn kurz vor Durchführung der Schätzung, die Fahrscene während einer kurzen Dauer (20ms – 200ms) durch ein weisses Bild abgedeckt wird. Da die Leuchtdichte des weissen Bildes in etwa gleich der mittleren Leuchtdichte der Fahrscene eingestellt wurde, ist davon auszugehen, dass der gefundene Effekt nicht auf die Störung der Lichtadaptation des Auges zurückzuführen ist. Die zunehmende Ungenauigkeit bei der Geschwindigkeitsschätzung könnte durch die Zunahme der mentalen Belastung bedingt sein, die durch die Verarbeitung der sich schnell ändernden, visuellen Umgebung entsteht. Somit würden auch Effekte der mentalen Belastung zum Unfallrisiko bei der Tunneleinfahrt beitragen. Um die mentale Belastung bei der Tunneleinfahrt zu minimieren, sollten die visuellen Umgebungen vor und im Tunnel möglichst einander angeglichen werden. Bei guter Sichtbarkeit des Tunnelinnern, könnten die herannahenden Autofahrerinnen und Autofahrer bereits vor Tunneleintritt mit der Verarbeitung der visuellen Umgebung beginnen, wodurch eine akut hohe mentale Belastung vermieden werden könnte. Eine gute Beleuchtung der Einsichtstrecke (z. T. auch Einfahrtstrecke genannt, ist die Strecke mit der Länge des Anhalteweges und die am Tunneleingang beginnt) ist wichtig! Die mentale Belastung liesse sich auch durch Verwendung von Fahrassistenzsystemen optimieren, mit denen eine Vorabinformation über das Tunnelinnere gegeben werden könnte.

In einem dritten Experiment konnte nachgewiesen werden, dass eine schnelle Änderung der Inhalte der visuellen Umgebung auch in der visuellen Peripherie zu einer Leistungseinbusse führt. Die Leistungseinbusse ist erheblich und vergleichbar mit der Leistungseinbusse, die durch eine Blutalkoholkonzentration von  $0.2 \text{ ‰}$  bis  $0.5 \text{ ‰}$  erzeugt werden kann. Oben erwähnte Massnahmen zur Verhinderung der Leistungseinbusse durch schnell variierende Inhalte der visuellen Umgebung lassen sich auch zur Verhinderung der Leistungseinbusse im peripheren Gesichtsfeld anwenden.

Die Autofahrerin bzw. der Autofahrer sieht die visuelle Umgebung als bewegt. Diese Bewegung erzeugt auf der Netzhaut einen sogenannten optischen Fluss. Der optische Fluss kann wesentlich zur Güte beitragen, mit der eine Fahraufgabe gelöst wird. Eine

Änderung in der visuellen Umgebung, z.B. beim Einfahren in den Tunnel, erzeugt eine Änderung des optischen Flusses, was sich wiederum auf die oben erwähnte Güte auswirkt. Somit könnte die durch die Tunneleinfahrt bedingte Änderung des optischen Flusses ein zusätzlicher Risikofaktor für Unfälle an Tunnelportalen sein. Zur Überprüfung dieser Annahme könnte die Änderung im optischen Fluss bei der Einfahrt bestehender Tunnels untersucht und mit den entsprechenden Unfallraten an Tunnelportalen korreliert werden. Hierzu müsste eine Methode entwickelt werden, um den optischen Fluss aussagekräftig zu quantifizieren. Als Beispiel einer möglichen Methode wird hier die Analyse mittels Spektrogramm (zeitlicher Verlauf des Fourierspektrums) vorgestellt.

An sonnigen Tagen kann bei der Einfahrt in den Tunnel die Lichtadaptation des Auges stark gefordert sein, da sich das Auge rasch an grosse Unterschiede des Lichtniveaus anpassen muss. Die Sichtbarkeit hängt u.a. vom kurzzeitigen ( $< 2$  s) Verlauf der Lichtadaptation (transiente Adaptation) ab. Gemäss den Resultaten unseres vierten Experimentes müsste der Leuchtdichtekontrast (Weber-Kontrast) von Objekten in der Einsichtzone um das Fünf- bis Zehnfache erhöht werden, damit Objekte in der Einsichtzone vergleichbar sichtbar werden, wie die Objekte vor der Tunneleinfahrt. Übereinstimmend mit Resultaten anderer Forschung, konnten wir nachweisen, dass eine Erhöhung des Lichtniveaus des Objektuntergrundes signifikant die Sichtbarkeit der Objekte verbessert. Unser Experiment wurde unter vergleichbaren Lichtverhältnissen durchgeführt, wie sie beim Uetlibergtunnel an einem sonnigen, wolkenlosen Tag gemessen worden sind (hier nicht wiedergegeben). Die Ergebnisse sprechen dafür, dass eine Erhöhung der Tunnelbeleuchtung in der Einsichtzone die Sichtbarkeit verbessert und somit zur Reduktion des Unfallrisikos beiträgt.

### **Vorschläge für weitere Arbeiten zur Verbesserung der Verkehrssicherheit auf Schweizer Strassen:**

- Erweiterung der hier berichteten statistischen Analyse durch Einbezug von Verkehrsunfällen bei weiteren Tunnelportalen in der Schweiz. Damit liessen sich weiterer Faktoren mit hinreichender statistischer Sicherheit untersuchen.
- Erstellung einer Karte, aus der kritische Strassenabschnitte im Schweizer Strassennetz ersichtlich sind, bei denen aufgrund der topographischen Gegebenheiten, des Tages im Jahr und der Tageszeit ein erhöhtes Unfallrisiko durch Sonnenblendung besteht.
- Umsetzung der für den Gubristtunnel vorgeschlagenen Alarmmassnahme bei Gefahr durch Sonnenblendung. Erfassung der Auswirkungen der Massnahme über eine längere Beobachtungsdauer.
- Umsetzung der anderen, im Bericht aufgelisteten Vorschläge zur Reduktion des Unfallrisikos am Tunnelportal und Erfassung der Auswirkungen der Massnahmen über eine längere Beobachtungsdauer.
- Entwicklung einer Methode zur Quantifizierung des optischen Flusses bei der Tunneleinfahrt. Korrelation der Änderung im optischen Fluss mit Unfalldaten.
- Einwirkung auf Standards zur Tunnelbeleuchtung mit dem Ziel, die hier vorgeschlagenen Massnahmen in den Standards zu berücksichtigen.

Die Autoren danken der ASTRA und der Begleitkommission für ihre wertvolle Unterstützung.

## Résumé

La position du soleil est un facteur de risque! C'est le résultat d'une analyse statistique des accidents de la route qui se sont produits auprès des deux portails du tunnel du Gubrist. Le risque d'accident augmente quand la position du soleil est telle, que les automobilistes en s'approchant du portail, peuvent voire le soleil juste au dessus du portail. Aussi, pour ces automobilistes, le risque d'accident est élevé, quand ils pourraient être éblouis par des réflexions spéculaires de la lumière de soleil, causées par le portail. Pour minimiser le risque, la trajectoire du soleil, le coefficient de réflexion, l'orientation et la forme des portails doivent-être considérés lors de la conception d'un nouveau tronçon d'autoroute.

Quatre expériences de laboratoire ont été réalisées pour mieux comprendre la contribution de l'éblouissement au risque d'accident. Les expériences ont été conçues de façon à permettre d'obtenir des connaissances sur les causes de télescopage, un type d'accident fréquent en proximité des portails de tunnel.

Une première expérience, qui a été réalisée dans notre simulateur de conduite, a démontré, qu'une forte source d'éblouissement ( $28'720 \text{ cd/m}^2$ ), la quelle a été positionnée en proximité du regard tout droit ( $28^\circ$  en périphérie du champ visuel), non nécessairement trouble l'habilité d'estimer la vitesse d'une voiture précédente. Les résultats de cette expérience indiquent que, à part l'éblouissement, des autres facteurs pourraient contribuer au risque d'accident, comme la variation rapide de l'environnement visuel du conducteur.

L'effet d'une variation rapide de l'environnement visuel sur l'habilité d'estimer la vitesse d'une voiture précédente, a été exploré dans une deuxième expérience. Les résultats de la deuxième expérience ont montrés, que l'estimation de la vitesse d'une voiture précédente sera d'une précision réduite, dans le cas ou juste avant d'estimer la vitesse, la scène, sera masqué par un écran blanc pour une courte durée (20 ms – 200 ms). Comme la luminance de l'écran blanc a été choisie de manière de correspondre à peu près à la luminance moyenne de la scène de conduite, la réduction de la précision n'est probablement pas due à des troubles de vision, qui sont causés par le défaut d'adaptation temporelle de l'œil au niveau de luminance. L'imprécision pourrait avoir été due à une augmentation de la charge mentale causé par le traitement de l'information visuelle mouvante, qui se présente lors de la transition de l'extérieur à l'intérieur du tunnel. Dans ce cas, pour réduire la charge mentale lors de la transition, il faudrait adapter les deux environnements visuels l'un à l'autre. Par une bonne visibilité de l'intérieur du tunnel, les automobilistes qui se rapprochent au tunnel pourraient initier le traitement de l'information mentionné bien avant l'accès du tunnel. De cette façon, une forte charge aiguë pourrait être évitée. Un bon éclairage du tronçon initial du tunnel (zone d'entrée) est important! Une réduction de la charge mentale pourrait aussi être obtenue en utilisant des systèmes d'aide à la conduite permettant de présenter au conducteur une information concernant l'état de trafic actuel dans la zone d'entrée du tunnel.

Une troisième expérience a mis en évidence que la variation rapide de l'environnement visuel réduit aussi la performance dans le champ visuel périphérique. La réduction de la performance est importante et comparable à une réduction causée par une dose d'alcool menant à une concentration d'alcool dans le sang de  $0.2 \text{ ‰}$  à  $0.5 \text{ ‰}$ . Les mesures susmentionnées servant à prévenir la réduction de performance causée par la variation rapide de l'environnement visuel, seront aussi efficaces pour éviter la réduction de performance dans le champ visuel périphérique.

Les conducteurs aperçoivent l'environnement visuel en mouvement. Sur la rétine, ce mouvement produit un flux optique. Le flux optique est une information importante pour les conducteurs et peut déterminer le niveau de performance de conduite. Une variation de l'environnement visuel, par exemple au moment de la transition de l'extérieur à l'intérieur d'un tunnel, entraîne une variation du flux optique, ce qui peut influencer la performance de conduite. Par conséquence, la variation du flux optique à l'entrée du

tunnel pourrait être un facteur supplémentaire de risque d'accident. Une vérification de cette hypothèse pourrait être faite en corrélant la variation du flux optique avec le taux d'accident. Pour cela il serait nécessaire de développer une méthode valide de quantification du flux optique. Dans ce rapport nous présentons l'analyse par spectrogramme (déroulement temporel du spectre de Fourier) comme méthode possiblement applicable à la vérification de l'hypothèse sus mentionnée.

Par des jours ensoleillés, l'adaptation temporelle de l'œil au niveau de luminance peut être mise à rude épreuve, car l'œil du conducteur accédant un tunnel doit s'adapter rapidement à des fortes variations du niveau de luminance. La visibilité dépend surtout du déroulement à court terme ( $< 2$  s) de l'adaptation (adaptation transitoire). Selon les résultats de notre quatrième expérience, les contrastes (contraste de Weber) de luminances des objets dans la zone d'entrée devraient être quintuplés (5 X) ou même décuplés (10 X) pour atteindre la même visibilité que pour les objets à l'extérieur du tunnel. En concordance avec les résultats d'autres études, nous avons pu démontrer, que l'augmentation du niveau d'éclairage du fond des objets augmente nettement la visibilité des objets. Notre expérience a été conduite dans des conditions similaires que nous avons mesurées pendant un jour ensoleillé au portail du tunnel de l'Uetliberg (mesures non représentées dans ce rapport). Les résultats de notre expérience indiquent aussi que une augmentation du niveau d'éclairage dans la zone d'entrée du tunnel améliore la visibilité et par conséquent pourrait réduire le risque d'accident.

### **Propositions pour autres travaux à l'objectif d'améliorer la sécurité routière en Suisse:**

- Analyses statistiques considérant les accidents de la route auprès d'autres portails des tunnels en Suisse. De cette façon on pourrait analyser d'autres facteurs avec une fiabilité statistique suffisante.
- Elaborer une carte montrant les tronçons de route critiques avec un risque d'éblouissement élevé dont le risque a été déterminé sur la base de données topographiques, du jour de l'an et de l'heure du jour.
- Réalisation de la mesure d'alarme proposée pour le tunnel du Gubrist, par laquelle les automobilistes sont alertés dans le cas de risque d'éblouissement. Analyse des effets à long terme.
- Réalisation des autres mesures mentionnées pour la réduction du risque d'accident au portail et analyse des effets à long terme.
- Développement d'une méthode pour quantifier le flux optique à l'entrée des tunnels. Corrélation de la variation du flux optique avec le taux d'accident.
- Agir sur les normes concernant l'éclairage des tunnels afin que les mesures proposées soient respectées.

Les auteurs remercient l'OFROU ainsi que la commission de suivi du projet pour l'appui précieux.

## Summary

Sun position is an issue! A statistical analysis of traffic accidents occurring in proximity of the portals of the Gubrist tunnel revealed an increased risk of accident when the position of the sun is such as a driver could see the sun close above the entrance portal. Also, the risk of accident is increased when a driver accessing the tunnel could be glared by specular reflections of sunlight caused by the tunnel portal. In order to reduce the risk of accident, the position of the sun, reflectance, orientation and shape of tunnel portals should be considered when planning highway segments. The use of sun shielding measures could be considered, but, in the case of the Gubrist tunnel, shielding measures could probably not be installed efficiently. Alternatively, a system could be installed, which senses the actual conditions and alerts the driver accessing the tunnel in case of risky lighting conditions.

In order to investigate the contribution of glare to the risk of accident, four experiments were carried out in the laboratory. As the rear end crash is an important type of accident occurring at tunnel portals, experiments were designed such as to enable conclusions related to causes for rear end crashes.

Surprisingly, in a first experiment, we found that a source of strong ( $28'720 \text{ cd/m}^2$ ) glare which is placed close above the line of sight (about  $28^\circ$  in the periphery of the visual field) not necessarily reduces the ability to estimate the speed of a car ahead. Results of this experiment indicate that, apart the glare, other factors, such as effects of a rapid varying visual environment, may also contribute to the risk of accident when driving into a tunnel.

In a second experiment, effects of a rapid varying visual environment on visual performance were investigated in a driving simulator task. Again, the task consisted in estimating the speed of a car ahead. Results of this experiment show that visual performance is reduced when a uniform white screen is presented for a short (20ms – 200ms) duration immediately before carrying out the task. Since the luminance of the white screen was close to the average luminance of the scene presented in the simulator task, found effect is probably not due to effects of light adaptation of the eye. The drop in performance could be due to an increased demand of mental resources required for processing the variations in content of the visual environment as similarly is the case when a driver enters a tunnel. An increased demand in mental resources and demands due to the variation in level of light adaptation should be considered as two distinct factors affecting the risk of accident. In order to minimize demand of mental resources when entering a tunnel, variations in the visual environment should be made as smooth as possible. A good visibility of the interior of a tunnel enables a more convenient allocation of mental resources, as the driver entering the tunnel may take some time to process the visual environment inside a tunnel before entering the tunnel. Good lighting in the threshold zone (zone extending from the entrance of the tunnel to the stopping distance) is important. A convenient allocation of mental resources could also be achieved using driving assistance technology for informing the driver about the visual environment in the threshold zone.

In the third experiment, rapid varying visual environments were shown to affect negatively task performance also in the visual periphery. We estimate the drop in performance to be very important and similar to a drop in performance as caused by the intake of an important ( $0.2\text{/}\infty - 0.5\text{/}\infty$ ) dose of alcohol. Measures mentioned in previous sections of this summary would of course help in coping with the drop in performance in the peripheral visual field.

The visual environment is imaged into the eye. The projected visual environment may cause a sensation of motion, the so called optic flow, in the driver's eye. Optic flow is a piece of information used in the driving process. Variations in the visual environment cause variations in the optic flow. Therefore, when driving into a tunnel, variations in optic flow may add to other factors for risk of accident at tunnel portals. In order to investigate made assumption, the variation in optic flow when driving into a tunnel could be

correlated to the variation with accident rate. Such a task requires the development of a valid method for quantifying variations in optic flow. In this report we suggest a quantification method based on spectrograms (temporal variation of the Fourier spectrum).

On sunny days, the driver's ability to detect objects when transiting into a tunnel is reduced due to effects of transient light adaptation. Following results of our fourth experiment, the Weber-contrast of objects in the threshold zone should be increased by about 5 to 10 times when compared to objects outside the tunnel in order to maintain visibility constant. In agreement to findings of others, we showed that raising the luminance of the background of objects significantly contributes to improvement of performance in detecting visual objects. In our experiment, lighting parameters were matched to extreme conditions recorded during a sunny day before the south west portal of the Uetliberg tunnel (not reported here). As a consequence for practice we may conclude, again, that increasing the luminance at tunnel entrances could improve visibility and therefore could reduce the risk of accident.

### **Suggestions for further work aiming to improve traffic safety on Swiss roads:**

- Statistical analysis of tunnel accident records including data of accidents occurring at portals of other tunnels in Switzerland, therefore enabling a reliable consideration of additional risk factors
- Identification of critical segments in the Swiss road network by considering topography, time of day and day of year
- Development and realization of above mentioned system to alert drivers accessing the Gubrist tunnel in case of lighting conditions causing an elevated risk of accident
- Realization of the other improvements as mentioned above at the entrance of a selected tunnel and quantification of effects by means of a long term observation
- Development of a method for quantifying the optic flow at tunnel portals. Correlation of the variation of optic flow with accident rates
- Improve actual standards on tunnel lighting by considering findings achieved in this project

The authors wish to thank ASTRA and the monitoring committee of this project for their valuable support.

# 1 Project outline

The aim of this project is to investigate risk factors related to safety when driving into a tunnel. The main hypothesis tested in this project states that abrupt varying lighting conditions reduce performance in estimating correctly the speed of a heading car. The hypothesis is investigated by means of experiments which are carried out in a driving simulator. An additional experiment is devoted to assess contrast sensitivity during transient adaptation for a case of an extremely varying level of luminance such as measured at a particular tunnel portal.

In order to better understand possible risks, records of traffic accidents occurring nearby or inside tunnels were analyzed statistically.

## 2 Statistical analysis of accidents nearby tunnel portals

### 2.1 Work package overview

This work package aims to investigate the effect of daylight conditions and other, traffic and environmental related factors on accident frequency nearby tunnel portals.

Accident data records delivered by the police of the canton Zürich were combined with meteorological data and with traffic data. Statistical analysis was used to assess correlation of accident frequency with investigated factors. Scientific literature on tunnel accidents is searched and summarized.

From our analysis we conclude that the actual position of the sun plays a crucial role in accidents nearby the tunnel entrance. This finding is supported by the literature as sun glare has been shown to be statistically significant correlated with traffic congestion (Churchill et al. 2012). As we have shown, accident frequency rates are increased in the case the sun is either near to the visual axis of the driver or in the case when the position of the sun is such as to cause specular reflections on the tunnel portal which then glare the driver. As a consequence, low reflective surfaces (e.g. dark or deflecting surface) should be adopted at tunnel portal entrances. A careful alignment of the tunnel entrance could reduce the risk of accidents as well.

Risk of glare and preventive methods to reduce risk should be considered in the phase road segments are planned. Methods have been suggested in the literature by means of which sun glare related safety issues on high-ways may be estimated by considering the topography and the orientation of the high-way (Churchill et al. 2012, Jurado-Piña et al. 2010 and 2009). The method computes periods within a year, in which an elevated safety issue is expected on the analyzed segment. The method is helpful in planning a road segment and also for designing physical counter measures to prevent an elevated risk. The method could be easily adapted for planning and analyzing risk of sun glare issues in high-ways and other roads in Switzerland.

As reported in the literature, the accuracy in reporting tunnel accident data should be improved and standardized across a larger area of interest (CH, EU, worldwide). Similarly, meteorological and traffic data should be sampled without gaps. Compatibility of any kind of data should be considered when adopting new methods for recording.

## 2.2 Literature search

Two literature search were conducted, one using the data base of “Web of Science” and another using the database ARAMIS ([www.aramis.admin.ch](http://www.aramis.admin.ch)).

### 2.2.1 Literature in “Web of Science”

The combination “*Accident AND road AND tunnel*” was used to search “Web of Science”. The search revealed a total of 456 references. After excluding patents, the remaining 229 papers were scanned for relevant information helping in summarizing the literature reporting about statistical analysis of accident frequency occurring in or nearby tunnels. This process lead to the five contributions summarized below.

Yeung JS and Wong YD (2013) analyzed 608 road traffic accidents occurring in three express way tunnels in Singapore in the time between 2009 and 2011. All three tunnels are dual tube tunnels and each tube, with exception of one of the tubes, consists out of three lanes. One of the tunnels is a four lanes tunnel. The authors found that accident rates are higher at the entrance section (first third of tunnel length) of the tunnel than is the case for accident rates at the exit section (last third of tunnel length) of the tunnel. The lowest rate of accidents was found in the central section (middle third) of the tunnel. In entrance and exit zones the number of multi vehicle crashes is higher than compared to the number of multi vehicle crashes in the central section of the tunnel. Since apparently most multi vehicle crashes on expressways are rear-end collisions, the authors suggest the authorities to make driver assistant systems mandatory. By means of driver assistant systems, the distance to the car ahead can be controlled automatically.

In order to evaluate severe accident rates and social costs in tunnels, **Caliendo C and De Guglielmo ML (2012)**, analyzed 762 crashes which occurred in 195 unidirectional tunnels in Italy in the time between 2006 and 2009. In 172 tunnels two lanes and in 23 tunnels, three lanes were installed. In order to compare accidents in tunnels with accidents in open road, severe accidents which occurred on open road sections of the motorways containing aforementioned tunnels were included in the analysis. The results of the analysis showed that in about 2/3 of the tunnels, severe accident rates in tunnels are higher than severe accident rates in open road sections of the motorway and lower than in the remaining 1/3 of the tunnels. Results seem to encourage to avoid a variation in motorway cross-section in the transition from the open road to the tunnel in order to reduce accidents in this sections. Also the emergency lane should be included in the consideration about the variation of the cross-section. The authors attribute the important drop of accident rates when plotting the data as function of year to an increased installation of electronic speed control systems and to the introduction of the driving license with the demerit point systems in case of violation of the highway code.

In 2004, **Krausmann E and Mushtaq F** suggested a data-collection template promoting a structured collection of data on tunnel accidents and near misses. The template shall facilitate the reporting of tunnel accidents and near misses as according to article 15 in the directive EU 2004/54EC of the European parliament and of the council on minimum safety requirements for tunnels in the Trans-European Road Network. During the development of the data-collection template, it became evident to the authors that validated data on tunnel accidents are often not available, not accessible or not validated. To support this finding, the authors list seven references dating from year 2001 to 2004.

In their investigation, **Zhuang-Lin M et al. (2009)** included 134 data sets about tunnel accidents. The accidents occurred in four freeway tunnels in China during the years 2003 – 2004. The four tunnels were two-tubes tunnels for one-way traffic. Each tube consisted out of three lanes. The tube lengths ranged from 200 m – 2949 m. Accident analysis was carried out as function of the location of the accident, time of the day and weather condition. Data were aggregated for location of accident considering four zones. The first zone extended from 100m before the tunnel entrance to the tunnel entrance, the second zone from the tunnel entrance to 100 m after the entrance, the next 300 m belonged to the third zone and the fourth zone was the remainder of the tunnel (in the paper also

termed as mid-zone). The frequency of multivehicle accidents increased with zone. For single vehicle accidents, the frequency of accidents before the tunnel (zone one) was higher than the one occurring at the first 100 m after the tunnel entrance (zone two). Frequency of single vehicle accidents increased monotonically from zone two to four. The highest accident frequency was found in the month of January. Accident frequency peaks three times within a day somewhere between 5 am – 7 am, between 9 am – 10 am, and between 3 pm – 5 pm. The authors suggest that accident rates may be reduced by improving the design of the tunnel entrance and by improving the illumination. Unfortunately it is not clear which illumination the authors refer to.

Much attention has been paid to **Amundsen FH and Ranes G** (2000) study on traffic accidents occurring in Norwegian tunnels. Amundsen et al. selected 587 road tunnels in Norway and analyzed a total of 499 person injury accidents occurring during a five year period from 1992 – 1996. Accidents were grouped in four zones according to the location of occurrence. Zone 1 covered 50 m beyond (before) the tunnel opening, zone 2 covered the first 50 m inside the tunnel, zone 3 the next 100 m inside the tunnel, and zone 4 the rest (mid.) of the tunnel. About 25% of the total number of accidents took place before the tunnel in zone 1. Half of the remaining accidents occurred within 150 m from the opening. The accident rate (ratio between number of accidents per year and number of vehicle kilometer driven) increased monotonically with progressing zone. The accident rate before the tunnel (zone 1) was about three times higher when compared to the accident rate in the mid-zone (zone 4). Both, average accident rate of zone 1 as well as average accident rates over all 4 zones are well below accident rates of two-way roads in Norway. From this finding the authors conclude that tunnels in Norway are not particularly accident-prone when compared to other road sections.

## 2.2.2 Literature in ARAMIS and other databases

Search of literature in the database ARAMIS was restricted to research projects belonging to either the ASTRA BST (ASTRA: Forschung Strassen-Brücken-Tunnel) or to the BFS (Bundesamt für Statistik). The search was based on the keywords “Tunnel” and “Unfall”. The search revealed a total of 103 projects. Except our own project, only the project **FGU2008/002 by Lellig C et al.** at a first glance appeared relevant to the purpose of statistical analysis of accident frequency in tunnels. However, FGU2008/002 deals about human factors aspects in the safety of tunnels rather than on statistical analysis of accident data.

A research work which is closely related to our topic has been reported by **Salvisberg U et al in 2004**. The authors report a statistical analysis of accidents which occurred on Swiss federal roads during the years 1992 - 2002. The total number of accidents increased from 7'685 in the year 1992 to 8'097 in the year 2002 with a peak of 9'094 in the year 1999. In the same period, tunnel accidents occurring on Swiss federal roads decreased from the peak number of 588 in 1992 to 570 in 2002. Among important findings were that in longer tunnels the accident risk per equal path length is lower than in shorter tunnels. In a long tunnel with a length of two times the length of a short tunnel the frequency of accidents is less than two times the one of a short tunnel (about only 1.6 times). Another finding reported by Salvisberg et al. is that the risk of accidents inside a tunnel is slightly lower than the risk of accident outside a tunnel. However, the risk to be involved in an accident inside a tunnel is higher than outside a tunnel, due to the fact that more people are injured in accidents occurring inside tunnels than in accidents occurring outside tunnels. As for the type of accident, Salvisberg et al. noted that rear-end collisions is the predominant (47% of all accidents) type in tunnels. The authors also conducted a survey among authorities in Switzerland about topics to be addressed in tunnel safety. Results of the survey revealed that a low lighting level in tunnels was the most frequent mentioned topic to be addressed in tunnel safety. In order to reduce the risk of accidents, the authors suggests including an adapting zone before the tunnel. The survey also revealed that most frequent named causes of tunnel accidents claimed by authorities.

It is worth to mention here that Salvisberg et al. also conducted a literature study on tunnel accidents. From their literature study the authors conclude that the topic of interest has received little attention in the literature. Literature summarized in Salvisberg's et al. work dates up to the year 2001 and has not been reported above. Therefore, findings about our literature search, and which are reported here, may be considered as complement to Salvisberg's et al. contribution.

## 2.3 Statistical analysis of tunnel accident records

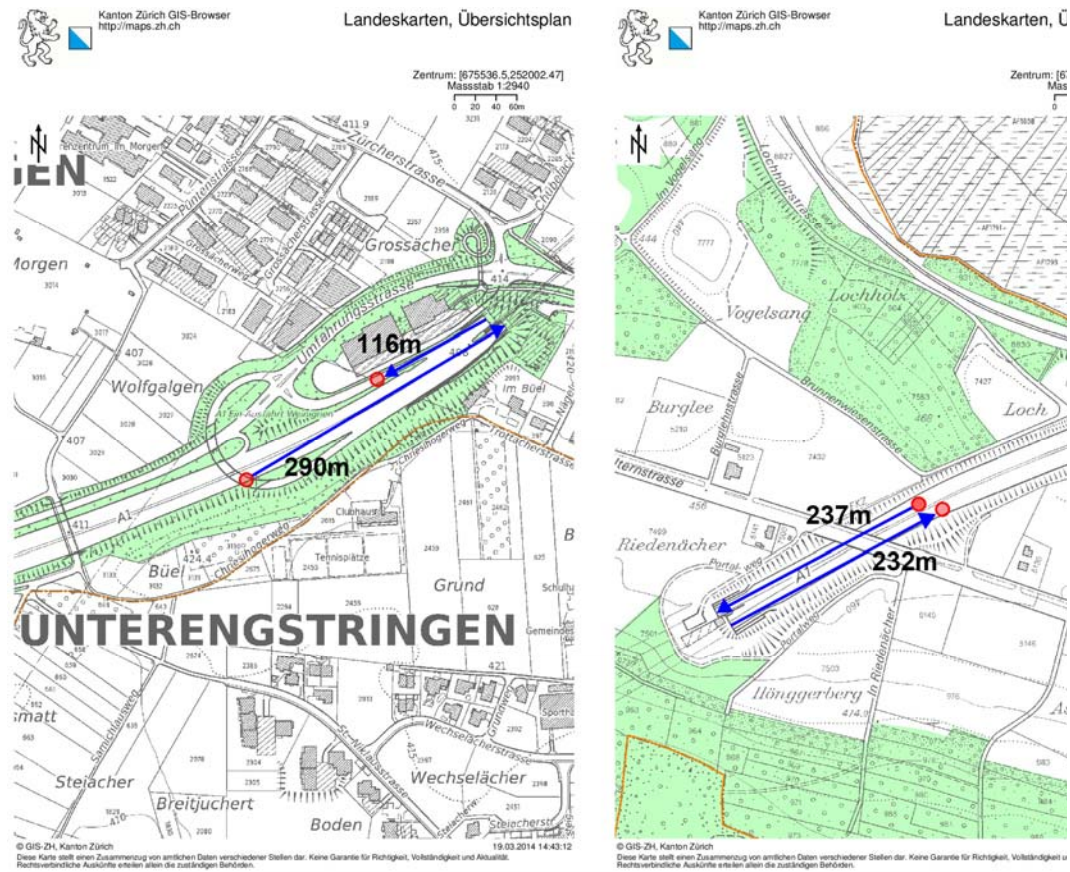
The main aim of this project is to assess the role of abrupt varying lighting conditions in car accidents occurring at tunnel entrances. Variations in lighting conditions at tunnel entrances may in part be due to the difference in light levels caused by the natural lighting outside the tunnel and the artificial lighting inside the tunnel. A driver entering a tunnel may be exposed to glare resulting from direct sunshine or, as we reported in an expertise (Menozzi M, 2009), the driver is exposed to a high amount of glare caused by reflections of sunlight at the tunnel portal. The latter cause may have become an increasingly important factor as first, the visible surface in new tunnel portals has gained in size when compared to elderly portal surfaces and second, the reflection coefficient of concrete, the visible material used in many of the portals, has increased importantly within about the last 60 years. We therefore raise the hypothesis that the position of the sun relative to the driver's visual axis and relative to the tunnel portal contributes to the risk of accident at or nearby tunnel portals.

As a first attempt in investigating the above mentioned hypothesis, a master thesis (Mauch D, 2012) was undertaken. The master thesis aimed to collect information related to car accidents occurring in or nearby highway tunnels and to estimate feasibility of the investigation of abovementioned hypothesis. The following important information was assembled in the master thesis: accident records provided by the police of the canton Zürich, traffic volume data collected nearby highway tunnel portals and provided by ASTRA (The Federal Roads Office, Switzerland), meteorological data nearby the tunnel portals and provided by MeteoSwiss (The Federal Office of Metrology and Climatology, Switzerland).

For the four tunnels Gubrist, Stelzen, Uetliberg and Isisberg, accident records were available. The four tunnels are highway tunnels with separate tubes for each driving direction. Traffic volume and meteorological data were available for a subset of accident records only. Due to the recent start of operation, a relatively low amount of accidents have occurred in the Uetliberg and Isisberg tunnels. It was therefore decided to focus further work in the master thesis on the analysis of a subset of accidents occurring in the driving direction to Bern of Gubrist tunnel. The subset included data of 980 accidents occurring between the years 1995 and 2012. Based on this subset of accidents it was concluded that frequency of accidents is highest after entering the tunnel and in proximity of the tunnel portal. Also it was concluded that accident frequency is positively correlated to traffic volume (number of vehicles per time), that weekday accident frequency peaks on Saturday and that the number of accidents is most elevated in hours between 15:00 and 18:00.

Data collected in the master thesis as well as experiences made during the evaluation are used for a consecutive analysis. The analysis is based on accidents of both driving directions of the Gubrist tunnel, i.e. the driving direction to St. Gallen as well as the driving direction to Bern.

The most south-west accidents which were included in our analysis occurred 290 m (determined by means of the geographical coordinates) before the tunnel portal on the lane in direction to St. Gallen and 116 m after the tunnel portal on the lane in direction to Bern (Fig. 1). The most north-east accidents which were included in our data occurred 232 m after the tunnel portal on the lane to St. Gallen and 237 m before the portal on the lane to Bern.



**Figure 1** maps showing the north-east (map on the right hand side) and the south-west portals of the Gubrist tunnels. The red circles denote location of the accidents farthest to the portals.

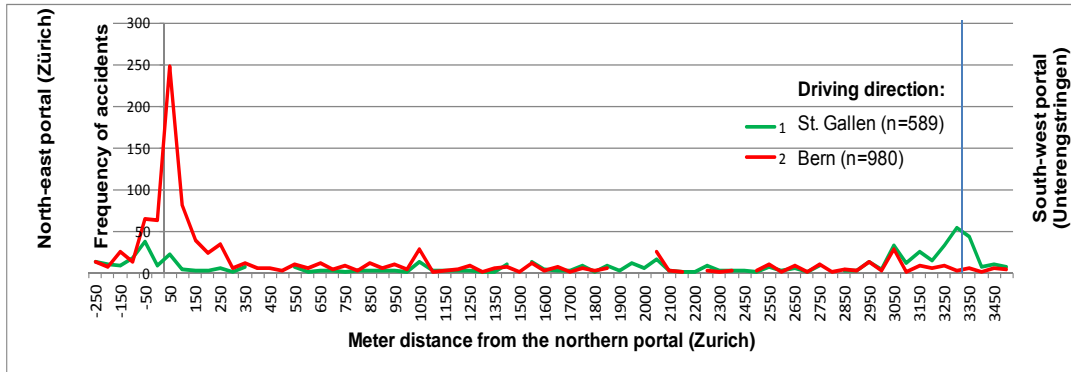
As listed in Tab. 1, a total of 1'569 accident records were included in the consecutive analysis, 589 of which occurring in the lane in driving direction to St. Gallen and the remaining 980 occurring on the lane in direction to Bern. For each accident, the exact location was retrieved from the corresponding police report, in which the location of the accident was reported by means of coordinates (swiss grid) as well as by means of the "police kilometers", the latter including the travel distance on the highway in kilometers relative to a fixed position. For the sake of convenience, the "police kilometers" is used whenever possible.

**Tab. 1** Number of accidents per driving direction occurring between 1995 and 2012 in or nearby the Gubrist Tunnel and which were included in our analysis.

Portal	Driving direction	Total records
Unterengstringen (south-west)	St. Gallen	589
Zürich (north-east)	Bern	980
Total number of accidents		1'569

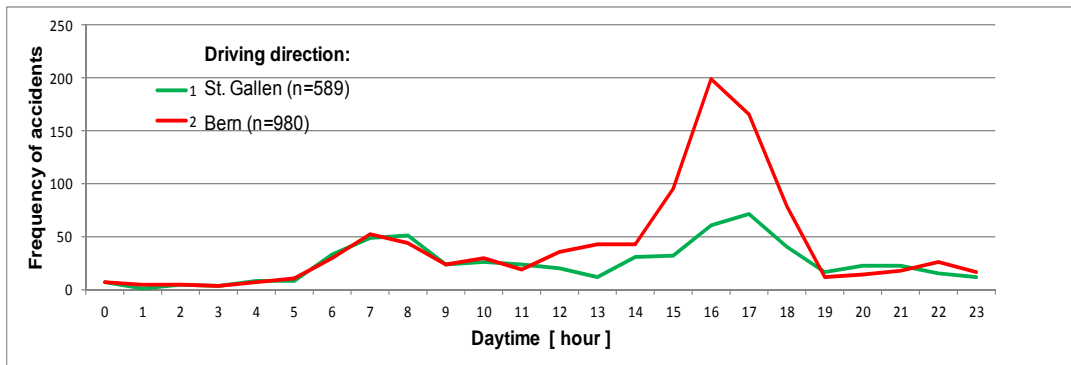
The accident frequency is plotted in fig. 2 as function of location of occurrence of the accident and for each driving direction separately. The north-east portal (Zürich) is used as origin of the plot (= 0 m) for the frequency distribution in both driving directions. The south-west portal (Unterengstringen) is at 3'300 m, according to the length of the tunnel. Events are binned in classes of a width of 50 m (classes: ..., -100m to -51m, -50m to -1m, 0m-49m, 50m to 99m, ...). For both lanes, accident frequency peaks within 50 m after

tunnel entrance. Peak frequency at entrance portal is 248 accidents in direction to Bern and 54 accidents in direction to St. Gallen which is about 25% and 9% respectively of the total number of accidents in the corresponding lane. As concerning the exits of the tunnel, a slight peak (38 accidents) is found on the lane in direction to St. Gallen whereas no elevated accident frequency is found on the exit of the lane driving to Bern.



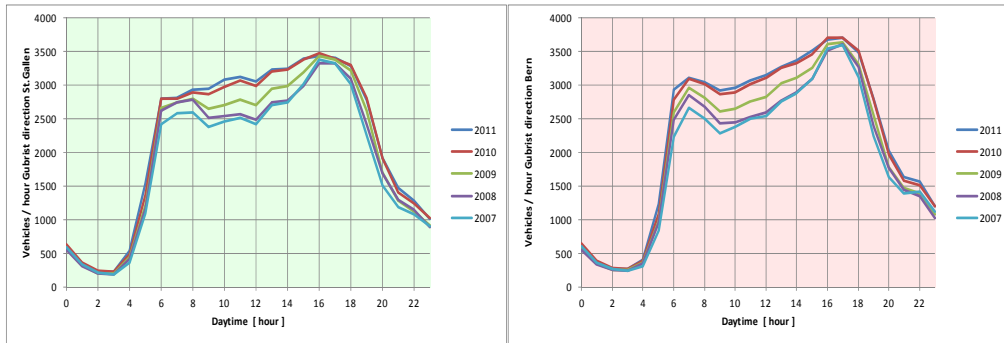
**Figure 2** Frequency distribution of accidents occurring in the Gubrist tunnel during the years 1995-2012 (in total 1'569 accidents). Accidents have been binned in sections of 50 m length. The two vertical lines denote the location of the tunnel portals. The green and the red lines denote data for the driving directions to St. Gallen and to Bern respectively.

Figure 3 reports the accident frequency as function of daytime. Data have been binned in 1 hour classes. In both lanes, peaks are noticed at about 7:00 and between 16:00 and 17:00. The ratio of accident frequency of the afternoon and morning peak is about 4.0 and 1.3 for accidents on the lane to Bern and on the lane to St. Gallen respectively.



**Figure 3** Variation of accident frequency with daytime of accidents occurring in the Gubrist tunnel during the years 1995-2012 (in total 1'569 accidents) binned by hour of day. The green and the red lines denote data for the driving direction to St. Gallen and to Bern respectively.

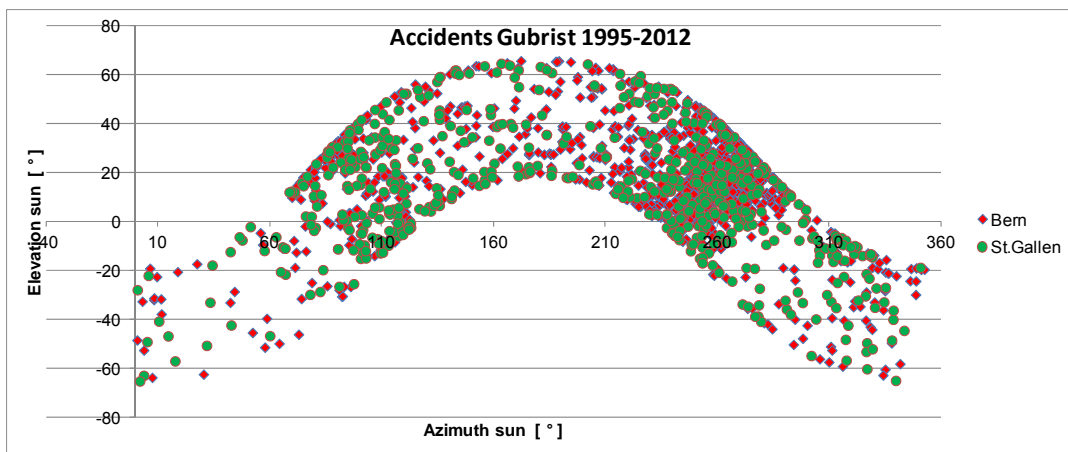
Traffic volume data of vehicles crossing the Gubrist tunnel were estimated by means of data recorded by the traffic monitoring station AVZ 287 at coordinates 678935/253196 located at a distance of 170 m from the north-east portal (lane direction to Bern). Unfortunately accessible traffic volume data do not cover all years of accident records included in this study. As can be seen in fig. 4, in both lanes peak volumes appear at 7:00 and between 16:00 and 17:00. The ratio of traffic volumes at the afternoon and the morning peak is roughly about 1.25 in both lanes.



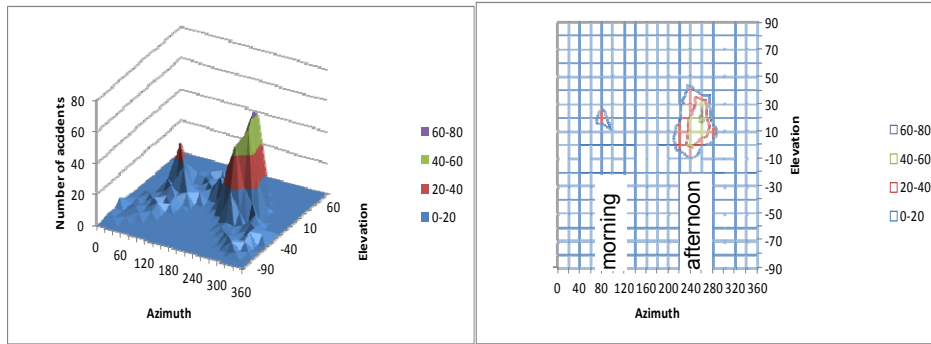
**Figure 4** Week average of hourly traffic volume in Gubrist tunnel as function of daytime for the traffic. Left graph lists data for the traffic in direction to St. Gallen and the right graph lists data for the traffic in direction to Bern.

As for the lane in direction to Bern the ratio between the afternoon and the morning peak traffic volume is 1.25. This value departs from the ratio between the afternoon and the morning peak accident frequency for the lane direction to Bern ( $\approx 4.0$ ) indicating that risk of accident is not linear correlated with traffic volume. Other factors, such as environmental or behavioral factors may contribute to risk of accident causing a non-linear relation between risk of accident and traffic volume. As for the environmental factors, the position of the sun could be considered. In the afternoon, a driver driving on the lane to Bern could easily be glared by the sun located close above the entrance of the north-east portal. As concerning behavioral factors, fatigue in drivers might be more elevated in the afternoon than is the case in the morning therefore increasing the risk of accidents in the afternoon. However, increased risk due to fatigue should be also be present in drivers driving in direction to St. Gallen and such an effect is not clearly visible as can be seen in fig. 3.

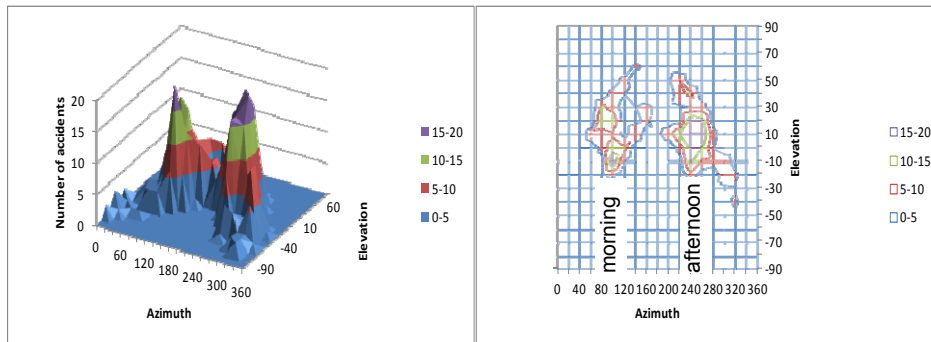
To further investigate the effect of sun glare on risk of accidents, accident events were plotted as function of sun position. In fig. 5 single events are plotted as function of azimuth and elevation of sun position at time the accident occurred and considering the coordinates of the location where the accident occurred. A more detailed descriptive analysis is plotted in the 3D frequency plots fig. 6 – 7.



**Figure 5** Accident events plotted as function of sun position at times and for the locations accidents occurred. Red diamonds denote accidents occurred on the lane direction to Bern and filled green circles denote accidents occurred on the lane direction to St. Gallen.



**Figure 6** Frequency distribution (left as 3D plot, right as iso-lines) of accidents on the lane direction to Bern as function of azimuth and elevation of sun position at time of accident.



**Figure 7** Frequency distribution (left as 3D plot, right as iso-lines) of accidents on the lane direction to St. Gallen as function of azimuth and elevation of sun position at time of accident.

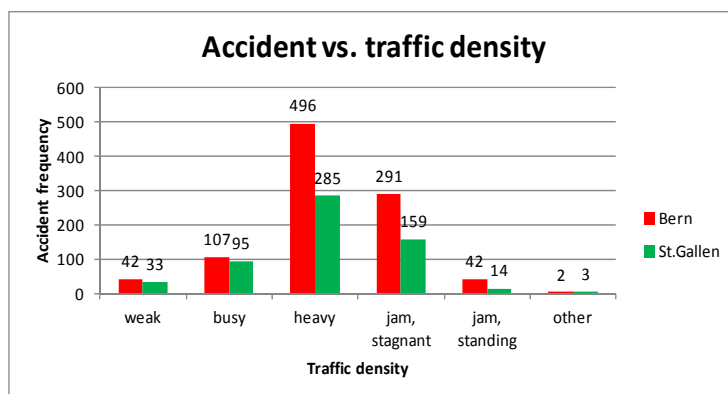
Again, one can assert that ratio of accident frequency between afternoon and morning peaks varies in the two lanes. The ratio is more pronounced in data of the lane direction to Bern than is the case for data of the lane direction to St. Gallen. An estimation of the center of the accident frequency distribution was computed by means of two separate cluster analysis one using the data recorded on the lane direction to Bern and the other using the data recorded on the lane direction to St. Gallen. As for the direction to Bern, the two clusters were found to be at the coordinates (azimuth / elevation) of (100.7° / 14.4°) for the morning cluster and (247.2° / 22.8°) for the afternoon cluster respectively with 260 accidents in the morning and 720 accidents in the afternoon cluster. As can be asserted by eye, the cluster coordinates fit well with the centers of the iso-lines in fig. 6. As for the direction to St. Gallen, centers of the morning and evening clusters are (104.7° / 11.5°) and (253.4° / 14.6°) with 255 and 335 accidents in the morning and afternoon cluster respectively.

Although automatic recorded traffic volume data is not available for all accidents considered in this report, an estimate of the effect of traffic density on accident frequency may be achieved by using the subjective estimate of traffic density of the reports which were recorded by the police. In the reports, traffic density is estimated on an ordinal scale considering the following six levels of traffic density: weak (code 190 in the police report), busy (code 191), heavy (code 192), jam stagnant (code 193), jam standing (code (194) and other (code 195). Tab. 2 lists the frequency distribution of accidents occurring in the two lanes and at the various levels of traffic density. Pearson's X2 test indicates that the frequency distribution significantly departs from being homogeneous (2-tailed,  $df=5$ ,  $\chi^2 = 15.225$ ,  $p=0.009$ ). The contingency coefficient of 0.098 ( $p=0.009$ ) indicates that there is no association between the variables traffic density and the lane. In other words, accident frequency of one lane at a given level of traffic density does not predict accident frequency in the other lane at the level of traffic density which again indicates that other factors than traffic density interfere with accident frequency.

**Tab. 2** Frequency distribution of accidents occurring in the two lanes of the Gubrist tunnel between 1995 and 2012 as function of traffic density (subjective ordinal scale).

Lane	Traffic density						Total
	Weak	Busy	Heavy	Jam stagnant	Jam standing	other	
Direction Bern	42	107	496	291	42	2	<b>980</b>
Direction St. Gallen	33	95	285	159	14	3	<b>589</b>
Total accidents	75	202	781	450	56	5	<b>1'569</b>

A histogram of data reported in tab. 2 is represented in fig. 8. The histogram indicates that accident frequency is positively correlated with traffic density when considering the levels weak, busy and strong. A decline of accident frequency is found in conditions of jam.

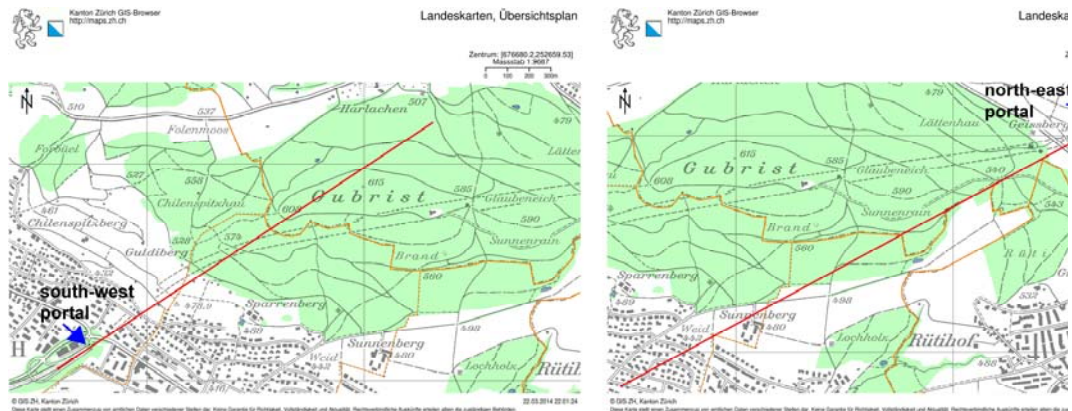
**Figure 8** Histogram reporting frequency distribution of accidents occurring in the Gubrist tunnel between 1995 and 2012 as function of traffic density (subjective ordinal scale) and as function of the two lanes.

The findings reported above indicate that in addition to traffic density other factors contribute to accident frequency. Among possible factors are fatigue, complexity of driving task, and exposure to glare. Most likely, fatigue is related to time of day. If effects of fatigue contribute in the same manner to accident frequency in both lanes, then, we would expect similar topography of the frequency distributions in fig. 6 and 7. Since this is not the case, fatigue can't be considered as an isolated factor in the risk of accidents. However, effects of fatigue could become visible when fatigue is combined with other risk factors (interaction effects). Investigation of interaction effects would require a detailed sampling of other factors possibly contributing to accident risks. For statistical reasons, a larger sample size than the one here available is required in order to investigate additional factors of risk.

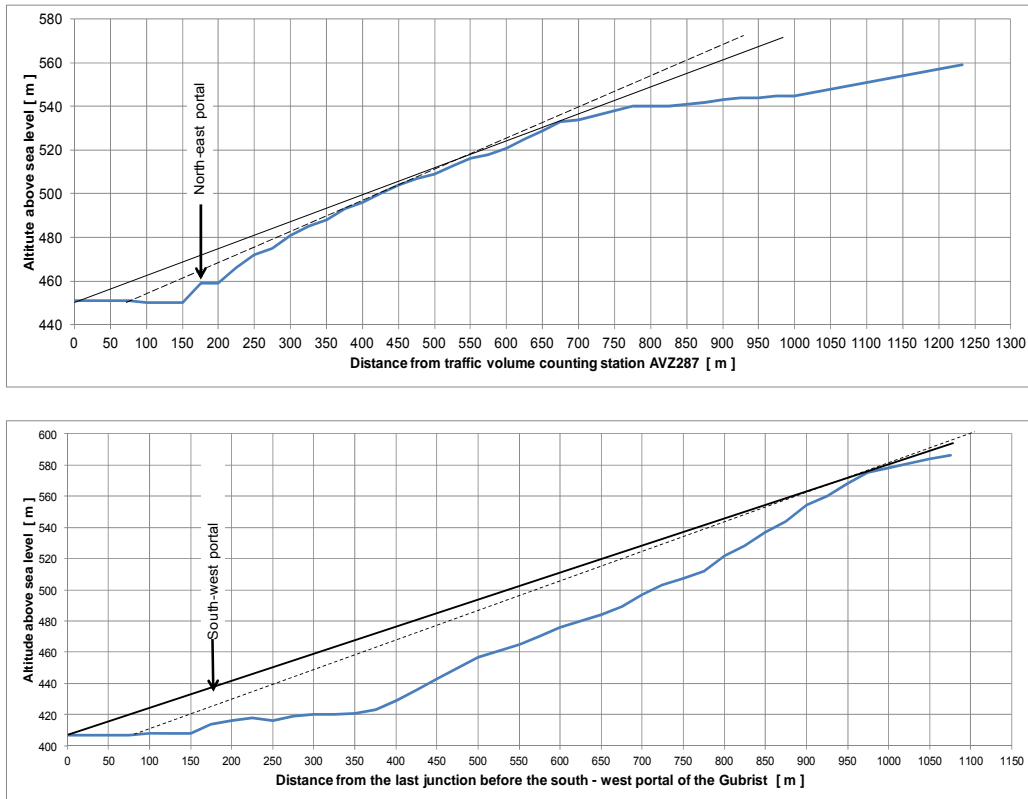
## 2.4 The role of sun position

Above reported findings indicate sun glare could play a role in accidents at the tunnel portal. Assuming a driver gazes straight forward, the risk of direct sun glare depends on the driving direction, the actual sun position and the topography as seen from the driver's position. Particular topographic shapes could act as a barrier shielding sun beams and preventing the driver of being glared. In the following we investigated risk of direct sun glare in driver's entering the portals of the Gubrist tunnel by considering the driving direction and the topography as seen by the driver.

Topography profiles were compiled using altitude data obtained from maps available at [maps.zh.ch](http://maps.zh.ch). Profiles as seen by the approaching driver were constructed by recording altitudes along the red lines depicted in fig. 9. The orientations of the red lines correspond to azimuth angles of  $242^\circ$  and  $66^\circ$  for the driving direction when accessing the north-east and south-west portals respectively. The starting points of the profiles were the traffic volume recording station AVZ287 for the base used at the north-east portal and the last incoming junction before the south-east portal for the base used at the south-east portal. Both starting points are at a distance of about 170 m from the corresponding portal. Altitude data was sampled in steps of 25 m (precision better than 1 m). Recorded altitude profiles are plotted in fig. 10. The black solid and dashed lines are tangents fitted by eye. The solid tangent originates at the starting points of the profile and dashed tangent originates at half way to the tunnel portal entrance. The estimated slopes of the tangents in the north-east portal are  $5.8^\circ$  and  $6.6^\circ$  respectively (fig. 10 top). Assuming altitude data is at soil level and adding about a 20 m high vegetation, the two slopes could slightly increase but are inferior to  $8.5^\circ$ . The slopes of the tangents in the bottom graph of fig. 10 (south – west portal) are about  $9.7^\circ$  and  $10.5^\circ$  and considering a vegetation of 20 m height, the two are below  $12^\circ$ .



**Figure 9** The red line denotes the bases along which the topographic profiles were recorded. The bases are oriented in direction of driving when approaching the corresponding portal. The starting point of the base used in the north-east portal is the traffic volume recording station AVZ287 (red circle on top right of the map on the left hand side) and the one of the base used in the south-east portal is the last junction before entering the south-west portal.



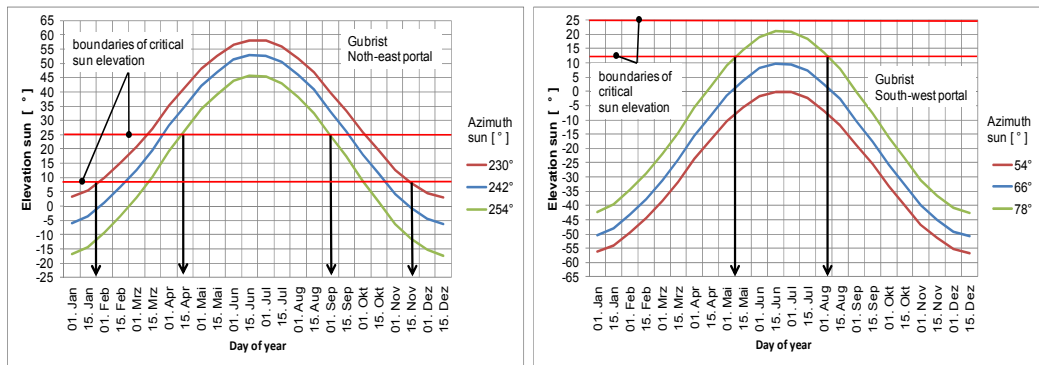
**Figure 10** Topographic profiles along the red lines depicted in fig. 9. Profiles recorded along the driving direction when approaching the north-east (top) and south-west (bottom) entrance of the Gubrist tunnel. Black solid and dashed lines are tangents fitted by eye originating from the starting point of the bases (solid line) and originating at half way to the tunnel portal entrances (dashed lines) respectively.

The elevation of the sun was computed for day 1 and day 15 of each month of the year. Elevations were computed for the two azimuth orientations corresponding to the directions of the driver when approaching the portal. Since sun glare for lateral sun positions may also be considered as critical, elevation data was also computed for azimuth directions lateral to the ones of the driving directions. The definition of the size of the critical visual field to be considered followed Juardo-Piña et al.'s (2009) considerations. Juardo-Piña et al. report that sun positions within  $19^\circ$  (for 40 years old drivers) and  $25^\circ$  (for 60 years old drivers) of visual field are considered as critical to the driver's safety. For the sake of simplicity we considered a rectangular instead of a circular critical visual field and computed critical sun positions for azimuth angles extending from  $0.5 * 25^\circ$  to the left to  $0.5 * 25^\circ$  to the right of the driving direction. The vertical extension of the critical visual field starts at direction of the tangent estimated using the topographical profile as seen from the driver (fig. 10) and ends at  $25^\circ$  above the horizon.

Sun positions were computed using public available formulas. Computed positions were confirmed using the reliable astronomy software [www.stellarium.org](http://www.stellarium.org).

From fig. 11 we may retrieve periods within the year in which the driver is exposed to critical sun. The left graph reports data for the north-east portal which are relevant to drivers on the lane driving to Bern. The right graph reports data for the south-west portal and is relevant to drivers driving in direction to St. Gallen. According to our computations the time of day in which the risk of being exposed to direct sun glare varies with day of year and is roughly between 15:50 (October) and 17:30 (March) at the north-east portal for driving direction to Bern and between 06:20 (Mai) and 07:00 (July) at the south-west portal in driving direction to St. Gallen.

As can be seen in the left graph of fig. 11, for the drivers driving to Bern there are two periods of time in the year, in which sun position may cause critical situations due to direct sun glare. The first period starts about in January 20<sup>th</sup> and ends about on April 10<sup>th</sup> and the second starts about the 1<sup>st</sup> of September and ends about the 15<sup>th</sup> of November. We therefore may conclude that the sun is located at critical position within the visual field of the driver approaching the north-east portal of the Gubrist for a total of more than 5 months per year. As for the driver approaching the south-west portal the critical period starts about the 7<sup>th</sup> of May and ends about the 5<sup>st</sup> of August, which then is a duration of about 3 months.



**Figure 11** Elevations of the sun at three azimuth positions as function of day of the year. The graph on the left shows data for the north-east portal of the Gubrist tunnel and the one on the right data of the south-west portal. Red lines denote boundaries of critical sun elevation and arrows mark the start and the end of the periods within the year, in which drivers might be exposed to an elevated risk of direct sun glare.

## 2.5 Discussion and conclusions

From what has been reported above we may conclude that there is an elevated risk of being exposed to critical direct sun glare during an important number of days of the year. At the north-east portal the elevated risk persists during the late afternoon, whereas at the south-west portal the elevated risk persists during the early morning.

In his review, Folkard S (1997) reported about “blackout times” in transportation safety. When plotting the mean trend in road traffic accidents as function of time (plotted as the z-score against the hour of day), Folkard noted peaks in risk to appear at 2:00, 14:00 and 21:00. Such peaks are not visible in our data (fig. 3 and 4). Among reasons accounting for the missing peaks, could be an overshadowing by much other stronger effects.

In order to reduce the elevated risk of direct sun glare physical and organizational measures have been suggested in the literature (e.g. Juardo-Piña et al. 2009, 2010). Roofing the access segment would not help much in the case of the Gubrist tunnel as it would only shift the elevated risk to other time windows and to segments of the highway which are before the access zone and, considering the terrain profile, such a measure could even worsen the situation. Another physical measure could be the reconstruction of the entrance portals in order to achieve a more favorable orientation of the portals.

As concerning organizational measures one may think of introducing a system to alert the driver during times of elevated risk and to introduce an adequate speed reduction and / or enforce a safe distance between following cars during critical times. Such organizational measures could be linked to an automatic detection of the elevated risk of sun glare eliminating false alerts and therefore improve acceptance of the measure in drivers.

## 2.6 Limitations of the study and outlook

Since computations made here are a rough estimation of the risk of direct sun at the entrance portals of the Gubrist tunnel, more detailed assessments should be carried out before planning and realizing any preventive measure.

Investigation of the role of lighting as a factor in accidents used in above study lacks from details on lighting at time of accident. As reported in Mauch (2012), lighting data rely on measurements taken several hundredth meters apart of north-east portal and apart of the location of accidents. Furthermore, only data on the horizontal illumination are available. Apart horizontal illumination at the location of the accident, a luminance profile as seen from the driver would help clarifying the potential risk of accident related to visual effects. Such a profile should be taken along the path of a driver entering a tunnel and for various lighting conditions. Such a profile would also be of interest in relating the utility of the adaptation luminance ( $L_{20}$ ) in estimation of accident risk for the tunnel entrances discussed in this report.

Although the number of accidents used in this report may be considered as high, for statistical reasons far more data is necessary when it comes to consider several more relevant factors and their combined effects on accident risk. As example, if the sun position, traffic density, weather condition, season, accident type, driver fatigue and driver behavior are considered each as a three level factor and, as a rough estimate, for statistical reasons at least five cases must be available for each combination of factors, then a total of  $3^7 \times 5 = 10'935$  cases are required. Probably such a high number of cases could only be achieved when merging data across Swiss highways which then would imply some efforts in standardized acquisition of the data (accident reports as well as relevant traffic data).

The role of driver behavior in causing an accident could be investigated using the videos recorded by surveillance cameras. Today, the computerized analysis of traffic video has achieved an impressive level. It would therefore be relatively easy to investigate accident risk caused by factors like speed variation or car to car distance and to compare the risk among different tunnels or different sections of tunnels.



## 3 Experiments in the driving simulator

### 3.1 Work package overview

The aim of this work package is to investigate effects of glare on a driver while accessing a tunnel. In order to investigate effects under a realistic driving scenario, experiments are run in our driving simulator. As reported in the literature (see section above) rear-end collisions are the most predominant type of accidents among tunnel accidents. We therefore focus our studies on possible effect of glare on the ability to detect speed of the car ahead. In a first experiment, drivers carry out a speed detection task while being exposed to strong disability glare ( $28'720 \text{ cd/m}^2$ ). Besides light adaptation, glare may affect cognitive (mental) demands in the driver entering the tunnel. In a second experiment, we therefore investigate effect of a mild glare (about  $10 \text{ cd/m}^2$ ) on performance in the same speed detection task as used in the first experiment.

Our findings showed an important effect of mild glare on cognitive demands in drivers. We therefore deepened our research and carried out a third experiment, aiming to assess effects of mild glare on performance in the peripheral visual field.

### 3.2 Effect of glare on speed discrimination

#### 3.2.1 Effect of disability glare

The following paragraph summarizes methods, results and conclusions of the experiment on disability glare. Additional details about the experiment can be found in an earlier paper which is included in this report as appendix 1.

##### Method

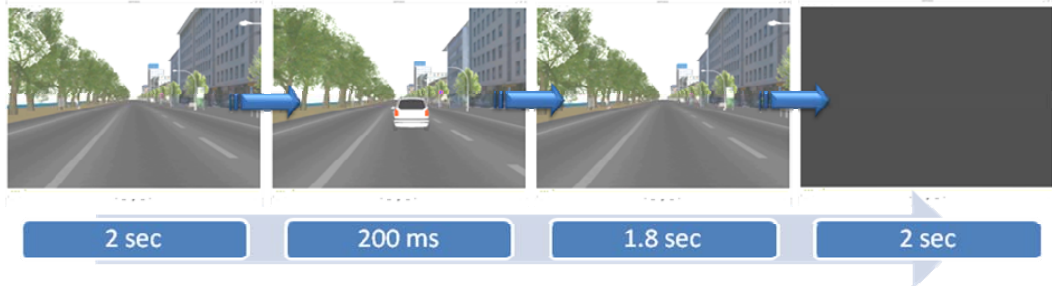
The effect of a strong disability glare on the driver's ability to discriminate speed of a car ahead was investigated in our driving simulator. The simulator consists out of a driver cabin, including a car seat, steering wheel, pedals, and projects a realistic simulated driving scenario (fig. 12) by means of a beamer on to a wall located at a distance of 3 m from the driver. Viewed from the driver's position, the projected scenario subtends a visual field of  $49.1^\circ$  by  $37.9^\circ$  (H x V).

In the purpose built realistic driving scenario the driver drives at a constant speed of 50 km/h along a straight city road. In the experiment, a car with a speed varying between 45 km/h and 54 km/h is presented ahead of the driver. The task of the driver consists in reporting whether the car ahead drove at a slower or at a faster speed than the speed (50 km/h) of the own car. In order to avoid the driver estimates speed differences between the car ahead and the driver's own car basing on long term comparisons, the presentation of the car ahead was limited to a duration of 200 ms.

Two conditions of glare were used in the experiment. In the first condition, no glare was used and in the second condition, a glare source was introduced in the upper right visual field of the driver. The glare was produced by an incandescent bulb (200 W) and was visible at an elevation of  $10.8^\circ$  and at an azimuth angle of  $25.4^\circ$  to the right of the sagittal plane of the driver whereas  $0^\circ$  azimuth angle denotes the direction of the driver's sagittal plane. The bulb was placed in a lamp housing which was oriented towards the driver. The exit of the lamp housing was covered by diffuse scattering screen. The glare source had a luminance of  $28'720 \text{ cd/m}^2$  and subtended an angle of  $5^\circ$  in the visual field of the driver. Computation of the unified glare rating (UGR) according to CIE 117-1995 revealed a UGR of 34, which, according to recommendations, is to be considered as intolerable.

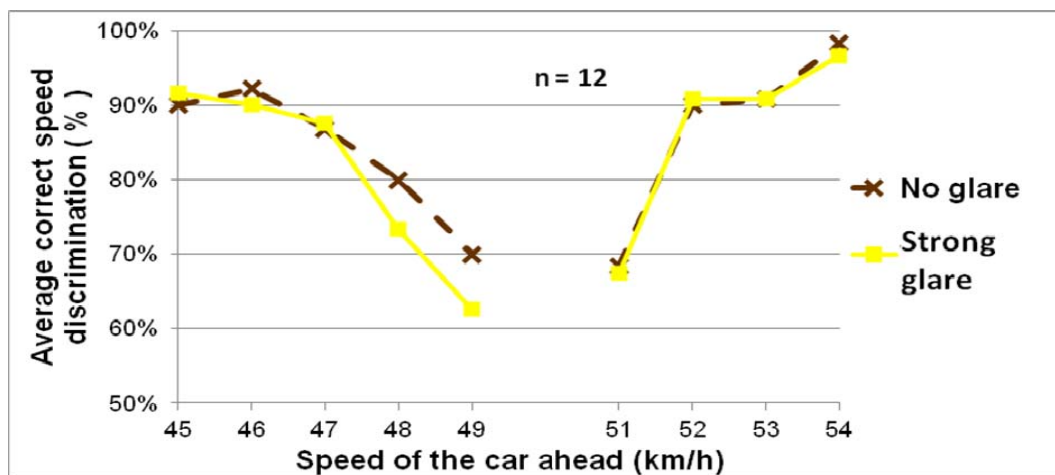
## Results

In the no glare condition, average luminances of the car ahead and of the background were  $21.6 \text{ cd/m}^2$  and  $1.5 \text{ cd/m}^2$  respectively, which results in a Weber contrast  $C$  ( $C = (L_{\text{Object}} - L_{\text{Background}}) / L_{\text{Background}}$ ) of 13.4. Due to stray light the two luminances increase by  $1.1 \text{ cd/m}^2$  each, which then reduces the contrast to  $C = 7.7$ .



**Figure 12** Sequences in the realistic driving scenario as seen from the subject. During an adaptation period of 2 s, the subject drives along a straight city road with a speed of 50 km/h. Immediately following the adaptation period, a car ahead is superimposed to the driving scene for 200 ms. In the following 3.8 s, the driver reports whether the car ahead drove at a faster or at a slower speed when compared to the speed of the own car.

Figure 13 reports the average percentage of correct detected speed differences in the two conditions of glare (“no glare” and “strong glare”). Data is based on results collected using 12 subjects. The age of the subjects ranged between 24 y and 55 y and none of them reported to have ocular diseases (cataract) which could be relevant to the experiment. As can be seen in fig. 13, effects of glare on average percentage of correct responses are small and are only visible, when the speed of the car ahead is inferior to the speed of the own car. The finding is supported by results of a two factorial ANOVA in which the two within-subject factors glare (two levels) and speed (9 levels) was considered. Glare was found to have no significant effect of average correct detections ( $F(1,11) = 3.085$ ;  $p=0.107$ , partial  $\eta^2 = 0.219$ ). In contrast, speed significantly affects average correct detections ( $F(8,88) = 12.126$ ;  $p<0.001$ , partial  $\eta^2 = 0.524$ ). There was no interaction ( $p=0.824$ ) between the factors glare and speed.



**Figure 13** Average percentage of correct speed discrimination for the two conditions of glare as function of speed of the car ahead.

## Discussion and conclusion

The ability to detect a difference between the speed of the car ahead and the speed of the own car varies with the absolute difference in speed. Following our results, the top

level of performance is already achieved at a speed difference of 3-4 km/h. When expressed in terms of Weber fraction and when top performance level is considered, the speed detection mechanism operates with a sensitivity of about 6-8%, which is of the order of sensitivity for other sensory mechanisms in human (e.g. Gescheider, 1971). As was shown by means of statistics, detection of speed in the case of a slower car ahead performs weaker than is the case when the car ahead drives faster than the own car. Performance in the speed detection task does not depend on the presence of the strong source of glare, which was used in our experiment.

Our results show that a source of strong glare not necessarily deteriorates the performance in detection of speed differences. This result of course depends on a couple of other factors such as the placement of the light source in the visual field, ocular properties, such as the presence of cataract, and gaze behavior of the driver. The presence of the strong source of glare would have probably affected performance of speed detection in subjects gazing into the glare source while or short before the detection task. The relevance of mentioned other factors in risk of accident is without any doubts important. However, it is reasonable to assume that a driver would tend to avoid an increased risk and therefore would avoid gazing into the strong glare in particular if the situation is presented with a high repetition rate as compared to our experiment. It is therefore also reasonable to assume that non-glare related mechanisms might have contributed to an increased risk in accidents investigated in the previous section. A candidate for such a mechanism could be related to the variation of visual content while entering a tunnel. A variation of visual content not causing a change in level of adaptation could bind processing resources in drivers entering a tunnel which then could be required in processing critical situations.

In order to compute the level of light adaptation in the driver's eye we compute the adaptation luminance  $L_{20}$  and add the average luminance of the projected scene. The light source used in our experiment subtends an angle of about  $5^\circ$  of the visual field and has a luminance of  $28'720 \text{ cd/m}^2$ . Considering a cone of an aperture of  $20^\circ$ , then the adaptation luminance  $L_{20}$  caused by the source of glare turns out to be  $(28'720 / 16) \text{ cd/m}^2$ . Adding the average luminance of the projected scene ( $23.1 \text{ cd/m}^2$ , while glare source on) to  $L_{20}$  results in an adaptation luminance of  $1'795 \text{ cd/m}^2 + 23.1 \text{ cd/m}^2 = 1'818.2 \text{ cd/m}^2$ . From experimental results reported by Greule (1993) we may consider a transition in the adaptation level to strongly affect the detection of a simple target on a uniform background. In our experiment a transition in the level of light adaptation from  $1'818.2 \text{ cd/m}^2$  to  $23.1 \text{ cd/m}^2$  was required, which is close to the condition in Greule's corresponding experiment, causing a strong deterioration of performance in detecting a simple target on a uniform background. The contrasting findings between our results reported in this section and Greule's results adds evidence to the hypothesis that a variation in visual information while entering the tunnel may affect visual performance even though variation takes place without any change in level of luminance adaptation of the eye.

Last but not least it should be mentioned that this finding bases on results of experiments run in the laboratory. Participants in our study might have concentrated more on accomplishing the detection task than would be the case persons driving in reality and not taking part in an experiment. Regardless the fact that there might be discrepancies between conditions in the lab and in reality, our results shows that when glare is present it is still possible to keep performance in detecting speed difference at the same level as it is the case when performing the task without glare.

### 3.2.2 Effect of discomfort glare

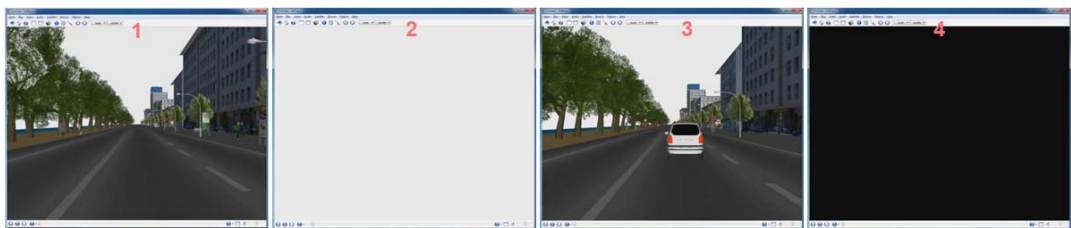
The following paragraph summarizes methods, results and conclusions of the experiment on discomfort glare using the same speed detection task as in the previous experiment, in which strong glare was used. In contrast to the previous experiment, the type of glare used here is such as not to affect light adaptation but rather to mask the visual

information before the speed detection task. Additional details about the experiment can be found in an earlier paper which is included in this report as appendix 2.

## Method

The experiment on the effect of discomfort glare on speed discrimination used the same driving scenario as in the experiment on the effect of strong glare on speed discrimination. A car was flashed for a duration of 200 ms ahead the drivers car. While the driver was driving at a constant speed of 50 km/h, the speed of the car ahead was varied from trial to trial ranging between 45 km/h and 54 km/h. The task of the subjects was to report whether the car ahead drove at a slower or at a faster speed when compared to the speed of the own car. In 50% of the trials, a white screen (RGB=255/255/255) was flashed (20 ms) before the car ahead appeared. The car ahead was displayed immediately after the white screen had disappeared. The sequence of scenes which were visible to the subjects is depicted in figure 14. In the first scene (number 1 in fig. 14) lasting 2 s the subjects drove at a speed of 50 km/h on an empty road. In scene number 2, either a white frame was presented for 20 ms, or the empty road was seen. Immediately after scene number 2, a car with a speed varying between 45 km/h and 54 km/h was introduced ahead of the driver. The car was visible for 200 ms and was presented at a virtual distance of 13.9 m from the subject. Subjects were asked to report as quick and reliable as possible whether the car ahead was driving faster or slower when compared to the speed of the own car. Additional details are given in appendix 2.

The average luminance of the driving scene is 8 cd/m<sup>2</sup>, the luminance of the white screen (inset number 2 in figure 14) is 16 cd/m<sup>2</sup>, and the luminance of the car popping up ahead is 12 cd/m<sup>2</sup>. Considering the small difference in luminances, it seems unlikely that effects of light adaptation in the driver's eye would affect performance in the speed discrimination task. Findings of the experiment on strong glare reported above support this statement. Further support to this statement is given by a pilot experiment, in which the luminance of the screen which is flashed before the speed discrimination task was varied. Results of the experiment with varied luminance of the white screen showed that a higher luminance of the white screen does not deteriorate performance in the speed discrimination task more than is the case when a white screen of a lower luminance is flashed.



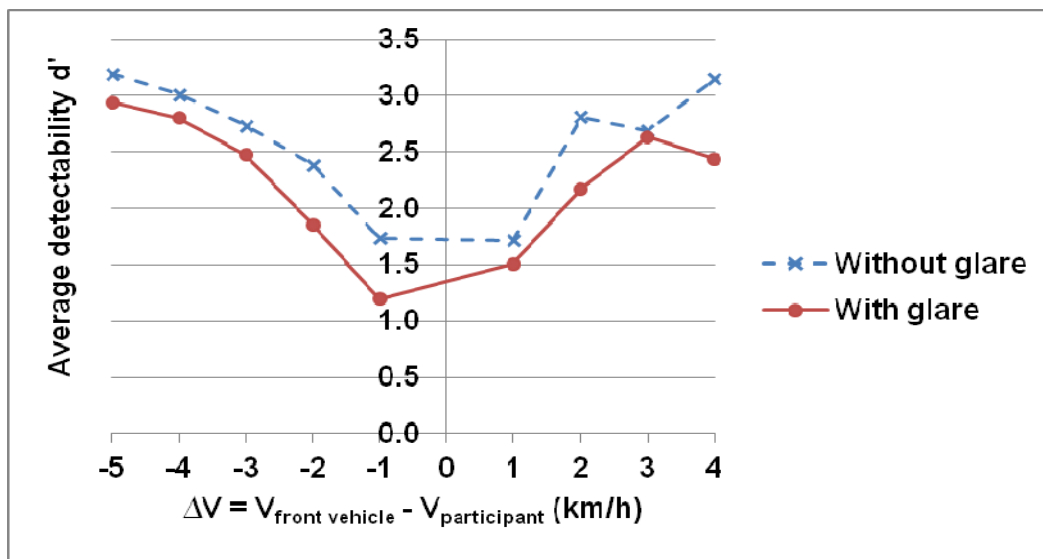
**Figure 14** Sequence of scenes as presented to the subjects in the experiment about the effect of discomfort glare on discrimination of the speed of a car ahead. The numbers in the scenes were not visible to the subjects. Scene 1: adapting phase (2 s); scene 2: in 50% of the trials a 20 ms white glare (16 cd/m<sup>2</sup>) was introduced; scene 3: a car ahead driving at a speed varying between 45 km/h and 54 km/h was introduced in the scene for a duration of 2 s; scene 4: a black screen was presented for another 2 s.

## Results

Performance in reporting whether the car ahead travelled at a faster or at a slower speed when compared with the speed of the driver's car is reported in terms of detectability  $d'$ .  $d'$  is a sensitivity measure derived from signal detection theory. A performance at chance level would result in a  $d' = 0$ . A "high" level of performance is achieved when  $d'$  adopts a value of about 3.0 or more.

As can be seen in fig. 15, average performance in the speed discrimination task depends on one hand on the difference between the speed of the car ahead and the speed of the driver's own car. On the other hand performance depends on whether glare, in the present case a white screen (2 in fig. 14), was introduced or not just before the speed discrimination task (3, in fig. 14).

Both factors, speed difference and presence of glare exert a significant effect on the driver's performance as shown by means of an analysis of variance (ANOVA) in which glare was considered as a two-level within-subject factor and speed difference was considered as nine-level within-subject factor. ANOVA results report a significant effect of glare ( $F(1, 12) = 8.021$ ,  $p = 0.015$ , effect size partial  $\eta^2 = 0.401$ , observed power = 0.739) and a significant effect of speed difference ( $F(8, 96) = 18.428$ ,  $p < 0.000$ , effect size partial  $\eta^2 = 0.606$ , observed power = 1.000). There was no significant interaction between the glare condition and speed difference condition ( $p = 0.299$ ).



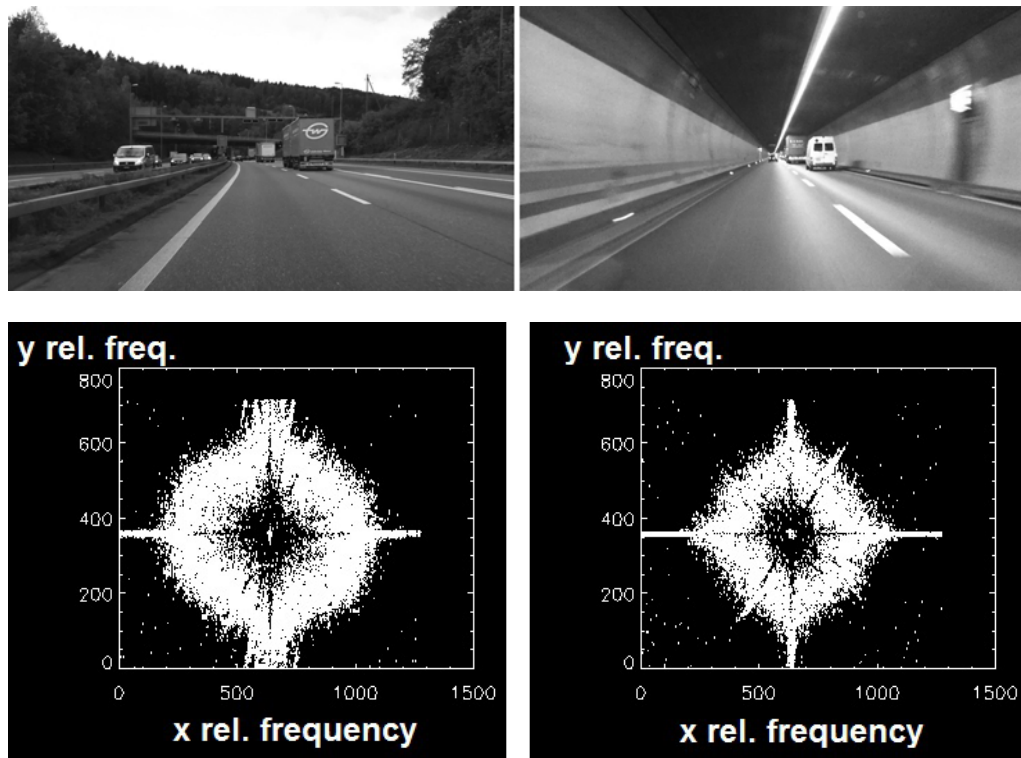
**Figure 15** Average performance in the speed discrimination task as function of difference between the speed of the car ahead and the speed of the subject's car and as function of presence of glare (white screen before the discrimination task).

### Discussion and conclusion

As reported above, presenting a white screen before the speed discrimination task significantly reduces performance in correctly estimating the speed of the car ahead. This effect is found although the luminance of the white screen ( $16 \text{ cd/m}^2$ ) is about the same as the average luminance of the driving scene ( $8 \text{ cd/m}^2$ ) and the luminance of the car ahead ( $12 \text{ cd/m}^2$ ). Therefore the white screen is not expected to have affected the driver's light adaptation.

Found effect could have been due to the masking effect of the white screen. Masking clears the visual memory requiring the brain to rebuild the visual memory after the white screen had disappeared. Such a process requires the allocation of resources. Since total available resources are limited (Wickens CD et al. 2003), the allocation of resources for rebuilding the visual memory comes at costs of available resources for other tasks, such as the speed discrimination task. As a consequence, process of rebuilding the visual memory and the speed discrimination task are competing on available resources. Therefore, the presentation of the masking white scene causes a drop in performance in the speed discrimination task.

A similar situation as depicted above may appear when transiting from one visual environment to another visual environment such as is the case when driving from outside a tunnel to inside a tunnel (see top pictures in fig. 16).



**Figure 16** Top pictures show the change in visual environment as may be seen by a driver transiting from the outside (left) to the inside of a tunnel (right). The corresponding spatial frequency distribution is shown in the graphs presented at the bottom (left for outside and right for inside).

Geometrical features visible to the driver transiting into the tunnel may undergo a strong temporal variation as indicated by the frequency spectra (bottom graphs in fig. 16) of the top images in fig. 16. This strong variation may require the brain to allocate resources for building up the new environment in the visual memory. As a consequence free available resources are reduced lowering performance in driving and therefore contributing to an increase in crash rate at tunnel entrances.

Geometrical features of the environment are projected onto the retina of the driver and generate a moving pattern. Features of such a moving pattern (optic flow) depend, among others, on geometrical features of the visual environment, speed and direction of motion of the driver. The literature reports a strong body of evidences about the role of optic flow in driving. For instance the driver may estimate parameters such as heading or speed based on properties of optic flow. Since variation of geometrical features in the environment cause a variation in optic flow, we may expect the estimation of driving parameter to be affected when entering a tunnel causing a variation in risk of accident at tunnel portals.

According to Wickens's "filter & resources" model (Wickens CD et al., 2012), allocation of resources is controlled by bottom-up and top-down mechanisms as well. Among others, top-down mechanisms assure availability of sufficient resources during prolonged tasks, such as for instance during a vigilance task (Mackworth NH 1948). One may argue that the white screen used in our speed discrimination experiment could be used by a top-down mechanism in order to efficiently manage resources and allocate resources required for the speed discrimination task only when needed. However, the presentation of a white screen caused a drop in performance. Possibly chosen experimental settings, such as luminance, duration and onset time of the white screen were not appropriate to cause above mentioned effect of trigger.

When the results are compared to the findings made in the previous experiment on disability glare, where a strong glare did not cause a drop in performance, we may state

that transitions in visual environments should be considered being at least as critical as possible effects of disability glare.

Among possible measures to cope with negative effects of transitions between different visual environments could be to improve visibility of interiors of tunnels so to give the driver a chance to familiarize with the interior of the tunnel before having accessed the tunnel. Alternatively, visualization systems such as augmented reality could be used to enhance visibility of tunnel interiors and prepare the driver to the coming changes in visual environment before she/he enters the tunnel.

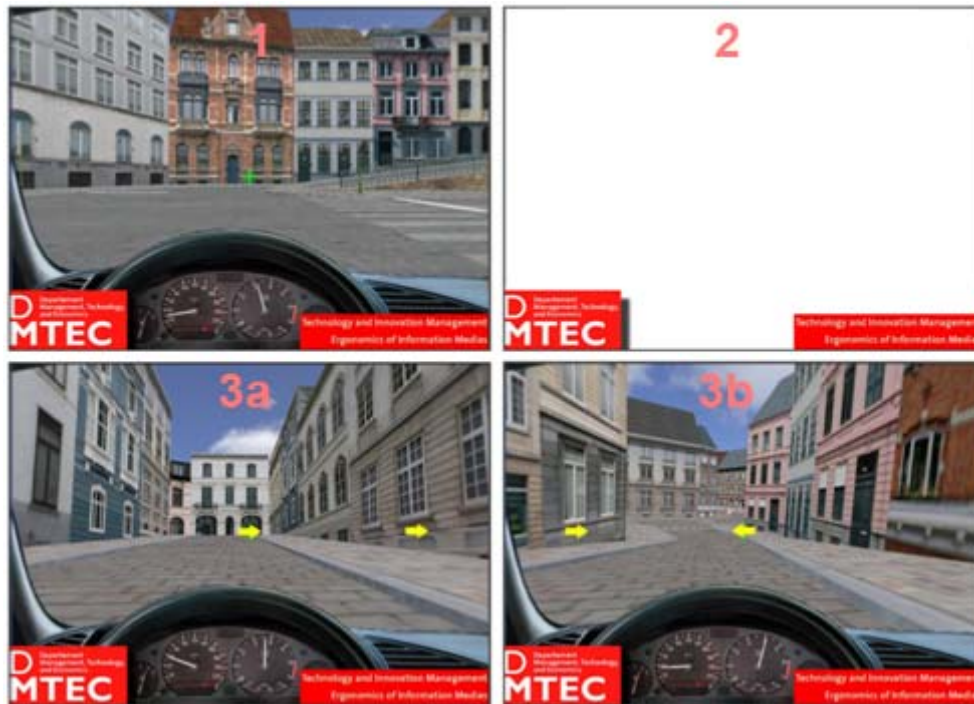
Finally we should consider including an analysis of transitions in the visual environment of a driver entering a tunnel as a factor contributing to the risk of accident at tunnel portals. Assuming that the strength in change of the visual environment is linked to the amount of resources required during the transition, we therefore may predict the risk of accident at the tunnel portal to be linked to the strength of change in visual environment. A possible method in defining the strength of transition in visual environment could be based on comparing a sequence of spectra (spectrogram) of driving environments as depicted in fig. 16. Another method could be to determine the variation of optic flow caused by the transition from outside to inside a tunnel. Such a method could account for visual properties varying across the visual field and therefore include a weighting of computed variations as function of the location in the visual field. For instance, variation of dynamic information could cause stronger effects when appearing in the peripheral visual field as when appearing in the central visual field. In contrast, variations of static information could be given more importance when appearing in the central visual field as when appearing in the peripheral visual field.

### 3.2.3 Effect of discomfort glare on peripheral visual attention

As mentioned above, the central and the peripheral retina are specialized in processing different types of visual information. In experiments reported above, we investigated effects of disability and discomfort glare in tasks, which were mainly relying on the processing of visual information in the central visual field. It is very well known that information processing in the peripheral visual field is very important in a driving task. We therefore set up an experiment to investigate the effect of discomfort glare on performance in processing peripheral visual information. Details about this experiment are given in a publication which is currently under revision. The publication is included in appendix 3 of this report.

#### Methods

The experiment on the effect of discomfort glare on performance in processing peripheral visual information was run in our driving simulator which has already been described in the previous experiments. The task in this experiment consisted in comparing the orientation of two arrows which were superimposed to a driving scene displayed on the projection wall of the simulator (fig. 17). One of the two arrows was presented in the center of the visual field and pointed to the location of the second arrow. The second arrow was presented at 18° in the visual periphery, either to the left or to the right of the central arrow. Subjects were asked to report whether the orientation of the two arrows was the same (as in inset 3a of fig. 17) or whether the arrows pointed in different directions (as in inset 3b of fig. 17). Only two possible orientations were used and the arrows could either point to the right or to the left. In order to prevent a foveal fixation of the peripheral arrow, a green fixation cross (see inset 1 in fig. 17) was displayed at the center of the scene and the peripheral arrow disappeared 200 ms after it has been displayed. In 50% of the trials, a white screen (see inset 2 in fig. 17) was flashed before onset of the two arrows. Further details on this experiment are given in appendix 3 of this report.

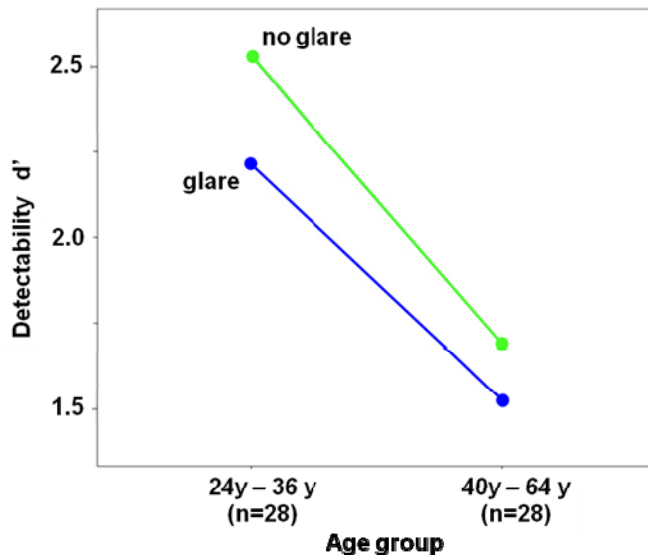


**Figure 17** Sequence in experiment about the effect of discomfort glare on processing peripheral visual information.

As we were able to show by means of a similar experiment (Menozzi M et al. 2012), age affects performance in processing peripheral visual information. Surprisingly, in the same experiment age did not affect significantly performance in processing information in the central visual field. This finding may be explained by a natural strategy adopted by the elderly to concentrate resources in processing information in the central visual field (“tunnel vision”). In the experiment about the effect of discomfort glare in processing peripheral information, effect of age was investigated by running the experiment in a group of young (24y-36y) and in a group of elderly (40y-64y) subjects.

## Results

Detection performance was recorded in 28 young (median age 29 y) and 28 elderly (median age 53 y) subjects. As can be seen in fig. 18, flashing a white screen before the task is lowering performance in both age groups. Performance as expressed by means of detectability  $d'$  is lower in both age groups when glare was introduced briefly before the task. In the young, mean  $d'$  were 2.21 (SD = 0.84) in the glare condition and 2.53 (SD = 0.91) in the no-glare condition respectively. In the elderly, mean  $d'$  were 1.53 (SD = 0.92) in the glare condition and 1.69 (SD = 1.30) in the no-glare condition respectively.



**Figure 18** Performance in detecting peripheral visual information when glare is introduced briefly before the task (blue line) and when no glare was presented before the task (green line).

A 2x2 ANOVA was run considering the two-level within-subjects factor of glare condition (glare and no-glare) and the between-subjects factor age. Results showed a significant effect of glare condition ( $F(1,1) = 6.793$ ,  $p = 0.012$ , effect size  $\eta^2 = 0.112$ , power = 0.726) and a significant effect of age ( $F(1,1) = 9.014$ ,  $p = 0.004$ , effect size  $\eta^2 = 0.143$ , power = 0.839). There was no significant interaction between the glare condition and age ( $p = 0.412$ ).

## Discussion and conclusions

In this experiment, we investigated the effect of discomfort glare on performance in processing peripheral visual information. When performance is expressed in terms of detectability ( $d'$ ), glare reduces performance by 0.32 in the young subjects and by 0.16 in the elderly subjects. By means of a similar experiment (Menozzi M et al. 2008) we were able to show, that the intake of a dose of alcohol resulting in a blood alcohol concentration of  $0.5\text{‰}$  results in a drop of detectability  $d'$  of about 0.5. This drop was determined using 14 subjects of an age ranging between 24 y and 56 y. Comparing the findings of the experiments with alcohol intake and the findings of the experiment on effect of discomfort glare on performance in processing peripheral visual information we may assume, that the drop in performance caused by discomfort glare is less but close to the drop a dose of alcohol could produce, which is at the legal (Switzerland) limit.

Results show that elderly are performing less good when compared to young subjects, no matter where glare was applied before the task or not. The effect of age reflects the strategy adopted by elderly to make better use of reduced availability of resources. Elderly tend to concentrate available resources in processing information in the central visual field. The strategy is at cost of performance in processing information in the peripheral visual field (“tunnel vision”). Such a strategy is probably not affected by the presence of glare, as effects of interactions between glare and age were not significant.

As discussed in the previous section we may consider the optic flow to be a visual phenomenon contributing to safety of driving. Because of efficiency of the peripheral retina in detecting time-varying stimuli, a drop of performance in processing peripheral visual information may importantly impair safety of driving.

Results of this experiment add evidence to the statement that discomfort glare may have a negative impact on the risk of accidents and should therefore be avoided.

In order to compensate for a drop in performance caused by discomfort glare one may improve the quality (saliency) of stimuli appearing in the visual periphery of a driver to make peripheral stimuli stand more out relative to neighboring items. In practice one could improve saliency of peripheral stimuli e.g. by increasing their number or by increasing their contrast (luminance or colour) or optimize their size. Such measures could be achieved by adding light sources or painting the interior walls of tunnels accordingly.

### 3.2.4 Experiment on transient adaptation

Strong glare causes visual discomfort and impairs certain visual functions. At tunnel portal areas, drivers are facing tough challenges when abrupt and strong light transition is involved. High-level glare may be seen in daytime conditions while driving towards the tunnel entrance. Direct sunlight and/or reflection of sunlight on the portal surface could affect drivers' performance while impairing visual ability. In comparison to the highly-illuminated exterior of the tunnel, the interior of the tunnel is usually at a very low luminance level. When entering a tunnel, such strong light transition causes adaptation problems of the eyes all in a sudden. One of the known issues is the reduced contrast sensitivity, which might be a critical factor regarding traffic safety concerns. Drivers might fail to see/detect the on-road objects clearly, e.g. the front car, traffic signs, the pavement, etc., and we might expect dangerous driving events to happen. Previous studies have shown that immediately after being exposed to high-level glare conditions, the contrast threshold in dark visual environment is increased. Increase in contrast sensitivity during the phase of transient adaptation, i. e. the phase between two levels of light adaptation, has been studied by Greule (1993). The effect has been shown to increase with step size of transition of luminance (Greule, 1993). Greule has examined contrast sensitivity for the light transition from 8'000  $\text{cd/m}^2$  to 8  $\text{cd/m}^2$ , and showed that the effect on contrast sensitivity loss is roughly seven times larger when compared to the effect at a transition from 2'000  $\text{cd/m}^2$  to 8  $\text{cd/m}^2$ . In our actual tunnel driving in Switzerland, an even much stronger light transition, e.g. from 14'000  $\text{cd/m}^2$  to 60  $\text{cd/m}^2$ , could cause severer impact on our contrast sensitivity. Such lighting transitions have been measured at the south-east portal of the Uetliberg tunnel (Menozzi 2009). By our knowledge the literature lacks from reporting about loss of contrast sensitivity during transient adaptation at higher luminance ranges as investigated by Greule (1993). Therefore we have conducted the transient adaptation experiment in order to better understand the contrast performance when encountering strong light transition as in the real case for tunnel driving.

#### Methods

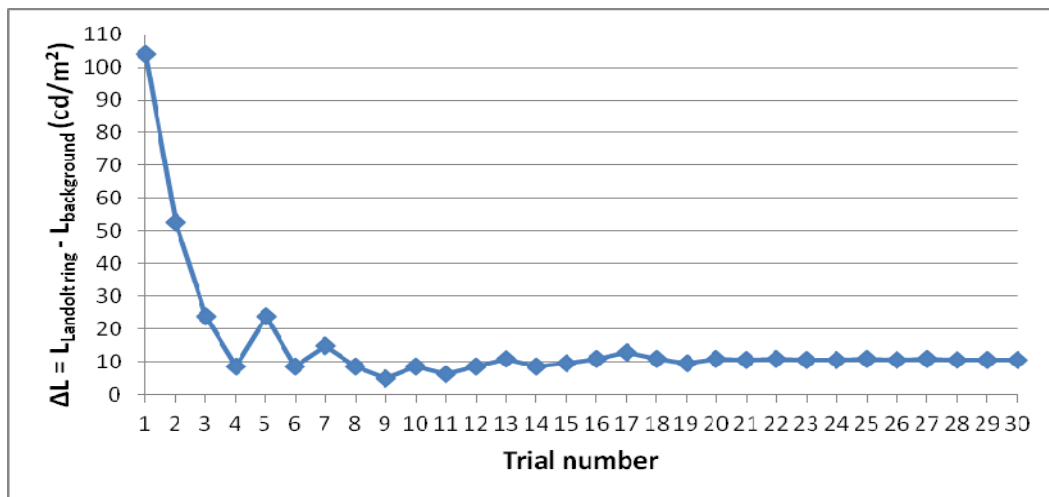
A laboratory transient adaptation experiment has been carried out in a dark room. The experiment required the participants to detect a visual target appearing shortly after the light transition took place, i.e. 100 ms and 500 ms (after exposure to glare), which varied in its contrast level. There were two light transition conditions applied: one was from 2'000  $\text{cd/m}^2$  to 8  $\text{cd/m}^2$  and the other was from 14'000  $\text{cd/m}^2$  to 60  $\text{cd/m}^2$ . The visual target used in this experiment was a Landolt ring with four possible orientations (up, right, down, and left) and corresponded to a decimal visual acuity level of 0.28. The optotype size of the Landolt ring was chosen based on the settings of Greule's studies (Greule, 1993). In our setup, the Landolt ring subtended a visual angle of 17.5' (minutes of arc) with the opening subtending a visual angle of 3.5'. In later sections, we are going to discuss our observations in comparison to Gerule's data sets where the target size was 20'.

Participants were guided to use the arrow keys on a keyboard to indicate the orientation of the Landolt ring being detected. Participants were seated at a distance of 50 cm to a projection panel (H x V : 20° x 15°). Two projectors (Acer PD321) with specific optical settings were used to project the viewing background from glare (2'000  $\text{cd/m}^2$  or 14'000  $\text{cd/m}^2$ ) transiting to darkness (8  $\text{cd/m}^2$  or 60  $\text{cd/m}^2$ ) and the target varying in various luminance levels superimposed centrally on the background. There were four sections in the main experiment. The first section was examining the required contrast threshold in a dark environment of 8  $\text{cd/m}^2$  and 100 ms after the glare exposure of 2'000  $\text{cd/m}^2$ . A total of 30 trials were included in the section. Each trial started with the full screen of glare

scene ( $2'000 \text{ cd/m}^2$ ) for 3 sec and then changed to the dark scene ( $8 \text{ cd/m}^2$ ). A Landolt ring was presented 100 ms after the background transitioned to the dark scene. The Landolt ring was presented for a duration of 50 ms. After the Landolt ring disappeared, the dark scene background remained for a duration of 2 sec and the subject was asked to report the orientation of the ring within this 2 sec. The orientation of the Landolt rings were chosen randomly. A staircase method was applied to alternate the luminance levels of the Landolt rings among the 30 trials. The other three sections were similar to the first section in principle. In the second section, the visual targets were presented 500 ms after the light transition from  $2'000 \text{ cd/m}^2$  to  $8 \text{ cd/m}^2$ . In the third section, the visual targets were presented 100 ms after the light transition from  $14'000 \text{ cd/m}^2$  to  $60 \text{ cd/m}^2$ . And in the last section, the visual targets were presented 500 ms after the light transition from  $14'000 \text{ cd/m}^2$  to  $60 \text{ cd/m}^2$ .

## Results

Experimental results from five participants (2 females and 3 males, 24y to 55y, mean age of 36.8y) were included in this report. All participants had normal or corrected-to-normal visual acuity, and wore their habitual corrections during the experiment, if applied. From each section, we have obtained the luminance levels of Landolt rings being detected among the total 30 trials based on the staircase method selecting process. For each participant, we have considered the average luminance ( $\Delta L$ ) of the last 5 turning points in the staircase procedure as his/her luminance threshold per condition. Figure 19 demonstrates an example from one participant performing the experiment in section 1. Figure 19 shows the target luminance as function of the trial number.

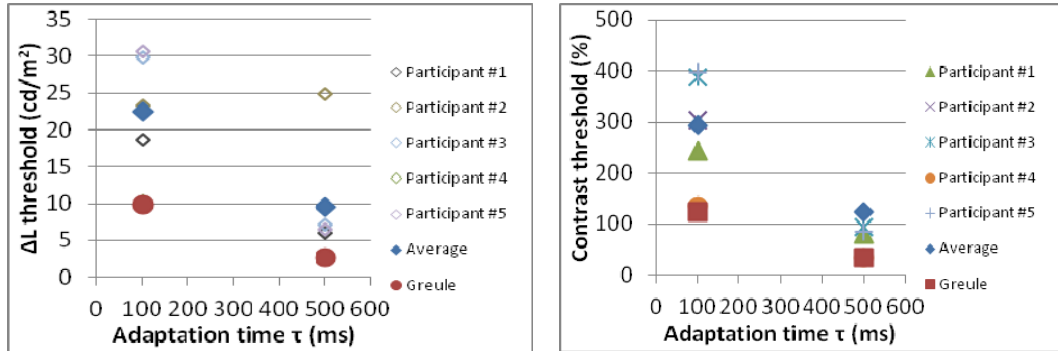


**Figure 19** Luminance variation among 30 trials from one single participant in experiment section 1 (light transition from  $2'000 \text{ cd/m}^2$  to  $8 \text{ cd/m}^2$ , visual target presented at  $\tau = 100 \text{ ms}$ ). The luminance difference  $\Delta L \text{ (cd/m}^2\text{)}$  equals to the luminance of the Landolt ring minus the background luminance.

Table 3 shows the average  $\Delta L$  thresholds among 5 participants under the light transition condition from  $2'000 \text{ cd/m}^2$  to  $8 \text{ cd/m}^2$  at  $\tau = 100 \text{ ms}$  and  $500 \text{ ms}$  after the light transition took place. Additionally, tab. 1 reports Weber contrast thresholds for the two conditions of target onset time ( $\tau$ ). In figure 20 we have plotted the experimental results graphically, in comparison with previous studies (Greule, 1993).

**Tab. 3** Average  $\Delta L$  ( $L_{Landolt\ ring} - L_{background}$ ) and contrast thresholds in experiments section 1 ( $\tau=100\ ms$ ) and section 2 ( $\tau=500\ ms$ ). Weber contrast  $C=\Delta L/L_{background} \times 100\%$ .

	Threshold expressed as $\Delta L$ ( $cd/m^2$ )	Threshold expressed as Weber contrast (%)
$\tau = 100\ ms$	22.53	292.6
$\tau = 500\ ms$	9.45	122.7

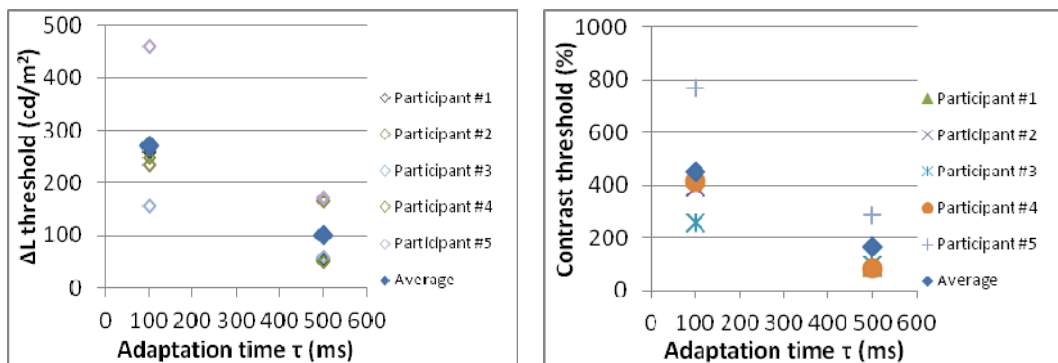


**Figure 20** Graphical representation of the measured  $\Delta L$  and contrast thresholds at two adaptation points. Reference points from Greule's measurement (1993) are given in the plots.

In table 4 we have shown the average  $\Delta L$  and contrast thresholds assessed in the light transition condition from  $14'000\ cd/m^2$  to  $60\ cd/m^2$  at two time points ( $\tau = 100\ ms$  and  $500\ ms$ ) after the light transition. And in figure 21 the experimental results are shown graphically.

**Tab. 4** Average  $\Delta L$  ( $L_{Landolt\ ring} - L_{background}$ ) and contrast thresholds in experiments section 3 ( $\tau=100\ ms$ ) and section 4 ( $\tau=500\ ms$ ). Weber contrast  $C=\Delta L/L_{background} \times 100\%$ .

	Threshold expressed as $\Delta L$ ( $cd/m^2$ )	Threshold expressed as Weber contrast (%)
$\tau = 100\ ms$	271.65	452.8
$\tau = 500\ ms$	99.62	166



**Figure 21** Graphical representation of the measured  $\Delta L$  and contrast thresholds at two adaptation points in the strong light transition conditions.

## Discussion and conclusions

In parts of the transient adaptation experiment, we were able to replicate the contrast sensitivity performance for low(-er) luminance visual environment as addressed in previous studies (Greule, Blackwell, Newacheck, Sturgis). Experimental results from this study showed quite a reasonable range of contrast sensitivity when comparing with others' observations for steady-state contrast sensitivity, thus revealed a convincing setup from our experimental designs.

In the weaker light transition situations, i.e. from 2'000 cd/m<sup>2</sup> to 8 cd/m<sup>2</sup>, the required liminal luminance difference of the visual target after 100 ms adaptation time was 22.53 cd/m<sup>2</sup>, which corresponded to a contrast threshold of 292.6%. When the eyes got more adapted to the dark environment, at 500 ms after the light transition, the contrast threshold then dropped to 122.7%, less than half at 100 ms adaptation time, where a lower contrast threshold indicates a better performance in contrast sensitivity. In other words, when car drivers are travelling from such light transition, the on-road objected are much more difficult to be detected/recognized right after entering the dark environment. In addition, we may notice that our contrast thresholds are higher than Greule's data at both adaptation points. There are some potential reasons which might have resulted in the difference between two data sets. For instance, the target size presented in our study was with an angular subtense of 17.5', which is 12.5% smaller than Greule's settings. We may expect a more difficult visual task to be performed in our study. This is in accordance with the higher contrast thresholds found in our data. Besides, the participants in Greule's study were highly-trained people for such visual tasks, and the participants included in our study were all newly-introduced to the test. This could be a main reason which led to the difference in the results.

In our daily tunnel driving, the light transition could be much stronger than the abovementioned cases. In the stronger light transition experiment sections, i.e. from 14'000 cd/m<sup>2</sup> to 60 cd/m<sup>2</sup>, at the adaptation time of 100 ms, we found the required liminal luminance difference of the target was increased to 271.65 cd/m<sup>2</sup>, which corresponded to a high contrast threshold of 452.8%. A higher contrast threshold shows a more critical situation in our contrast sensitivity function. This result shows that when car drivers enter a tunnel in a sunny day, for a short moment they are unlikely being able to detect their visual targets well. This could be a very dangerous and critical moment for the tunnel driving. After a 500 ms adaptation time from the strong light transition, the luminance difference threshold decreased to 99.62 cd/m<sup>2</sup>, which corresponded to a contrast threshold of 166%.

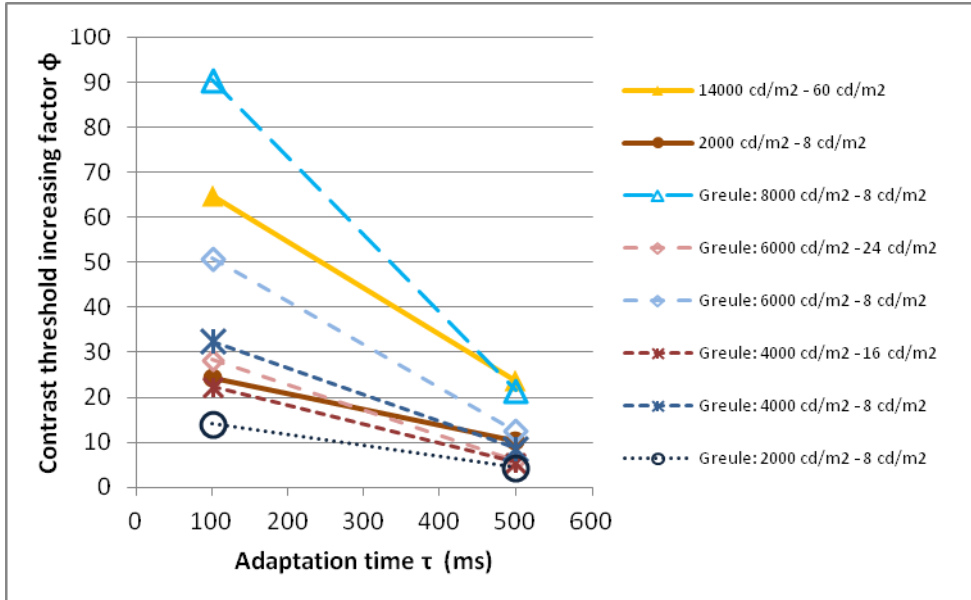
In order to compare our data to Greule, where Greule mainly used the contrast threshold increasing factor  $\phi$  for comparing the results in different transition conditions (Greule, 1993), we have taken the referenced steady-state contrast thresholds from previous literatures to assess the estimated contrast threshold increasing factor  $\phi$  in our experiments (Blackwell 1946, Newacheck 1990, Sturgis 1982). In Greule's study,  $\phi$  has been defined as the contrast threshold at adaptation time  $\tau$  divided by the contrast threshold after a 60 sec adaptation period. We have assumed the steady-state contrast thresholds of 7% and 12% at the background luminance levels of 60 cd/m<sup>2</sup> and 8 cd/m<sup>2</sup> respectively in our study.

In table 5 we have indicated the obtained  $\phi$  values from our experiments and from Greule, as in figure 22 the graphical presentation of the  $\phi$  has been shown. We would like to point out several major findings here. As we can see from table 5, when a fixed luminance level of the dark environment was given, i.e. 8 cd/m<sup>2</sup>, a larger  $\phi$  was shown when a stronger light transition took place. This is in accordance with our knowledge that a higher glare level would cause stronger effects on the adaptation mechanism and cause lower contrast performance. We may expect a much larger  $\phi$ , in comparison to the 8'000 to 8 cd/m<sup>2</sup> situation ( $\phi = 90.5$ ) from Greule's data, to be found in a 14'000 to 8 cd/m<sup>2</sup> case, if any. Another important finding from table 5 would be, when we fixed the light level of the glare source and changed the dark background luminance, we may notice that a better contrast sensitivity was achieved when the dark environment was set to a higher luminance level. Our current setting of a light transition from 14'000 cd/m<sup>2</sup> to

60 cd/m<sup>2</sup> showed an increasing contrast threshold factor of 64.7 at the adaptation time of 100 ms, and still as high as 23.7 at the adaptation time of 500 ms. As mentioned before, we would expect a  $\phi$  (much) larger than 90.5 in a light transition from 14'000 to 8 cd/m<sup>2</sup> at  $\tau = 100$  ms. As we have increased the darkness from 8 to 60 cd/m<sup>2</sup>, the contrast sensitivity has been significantly improved to 64.7. In our tunnel driving cases, we may not be able to change the strong glare from the sunshine, however, we may expect our contrast sensitivity performance improved by increasing the interior luminance level of the tunnel near the portal area.

**Tab. 5** The contrast threshold increasing factor  $\phi$  in different light transition conditions.  $\phi = \text{contrast threshold } C_T / \text{steady-state contrast threshold } C_{\text{steady-state}}$ . \* In Greule's data, the  $\phi$  was defined as contrast threshold  $C_T / \text{contrast threshold } C_{\tau = 60 \text{ sec}}$ .

Light transition conditions	$\phi$	
	$\tau = 100$ ms	$\tau = 500$ ms
From 14'000 cd/m <sup>2</sup> to 60 cd/m <sup>2</sup>	64.7	23.7
From 2'000 cd/m <sup>2</sup> to 8 cd/m <sup>2</sup>	24.4	10.2
*Greule: 8'000 cd/m <sup>2</sup> to 8 cd/m <sup>2</sup>	90.5	21.5
*Greule: 6'000 cd/m <sup>2</sup> to 24 cd/m <sup>2</sup>	28.4	6.0
*Greule: 6'000 cd/m <sup>2</sup> to 8 cd/m <sup>2</sup>	50.8	12.5
*Greule: 4'000 cd/m <sup>2</sup> to 16 cd/m <sup>2</sup>	22.4	5.6
*Greule: 4'000 cd/m <sup>2</sup> to 8 cd/m <sup>2</sup>	32.5	8.7
*Greule: 2'000 cd/m <sup>2</sup> to 8 cd/m <sup>2</sup>	14.1	4.4



**Figure 22** Graphical representation of the contrast threshold increasing factor  $\phi$  at two adaptation points.

From the strong light transition (14'000 to 60 cd/m<sup>2</sup>) cases in our experiments, which demonstrated an actual transition condition in our daily tunnel driving, we have found out the required contrast threshold at 100 ms after the light transition tool place was at a very high range of 452.8%. The on-road objects inside the tunnel must be much brighter, i.e. 4.5 times, than the background environment to be seen well or recognized. This shows us a very critical driving task near the tunnel portal area. Even when we have adapted to the darkness for 500 ms, i.e. corresponding to a travelling distance of 13.9 m at a speed

of 100 km/h, a contrast threshold of 166%. We still have a bad contrast sensitivity for retrieving the visual objects. We would suggest increasing the light level for the tunnel interior, especially near the portal area in order to improve the contrast sensitivity performance.

## Appendix

### I Papers

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## Paper 1: Strong glare and speed detection

### Effect of strong glare exposure on speed detection task in a simulated driving scenario

In: Gestaltung der Arbeit der Zukunft. GfA Press, Dortmund, 2014

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**Abstract:** among critical challenges in our daily driving, to avoid crashes with the front car is one major issue. Such crashes might happen when the car driver fails to see the front car clearly caused by bad visibility or insufficient attention, or misestimated speed of the front car. We conducted a simulated driving task and aimed to investigate the effects on speed detection caused by a strong glare source acting as the sun in the peripheral visual field. 12 participants performed the speed detection experiment under glare and no-glare conditions for various speed settings of the front car. Results showed no significant difference between the no-glare and the glare conditions. The glare setup in this study might arouse the alertness during the task and compensate for impaired visual functions.

**Keywords:** traffic safety, driving quality, visual performance, speed detection, attention, glare.

#### 1. Introduction

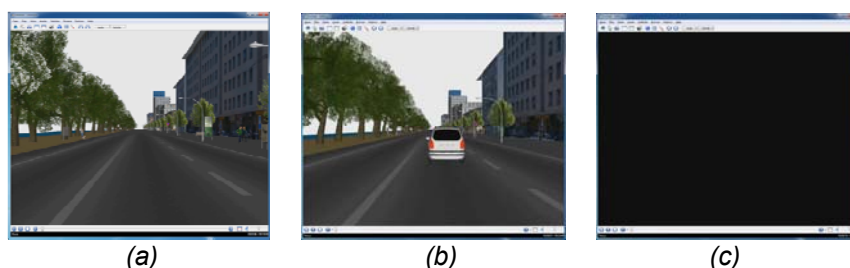
For traffic safety concerns and driving quality, we must keep top and stable driving performance on the road when facing various driving tasks under different environments. Among some critical challenges, to avoid crashes with the front vehicle is one key issue. Such crashes might take place when the car driver cannot clearly see the front vehicle due to bad visibility or lack of attention, and/or misestimates the speed of the front vehicle which results in insufficient safe following distance. In particular, glare may play a role in abovementioned issues while affecting the eye adaptation and disturbing the attention mechanism. Disability glare which is caused by light scattered in the eye may disable the visual system to some extent (Boyce, 2003) and increase the probability of a risky driving event. Such strong glare may reduce the road visibility as well as other objects on the road, e.g. the front vehicle, pedestrians, traffic signs, etc. Menozzi et al. (2013) reported an elevated risk for accidents in proximity of the tunnel portal on a Zurich highway based on a statistical analysis. The risk of accidents highly depended on the sun position and critical situations happened when the sun acted as a direct glare source or as an indirect glare source (reflection on the tunnel portal). Gray et al. (2007) reported that in simulated low-sun conditions, the time to collision (TTC) with approaching vehicles was overestimated by the drivers while performing left-turn driving tasks in a simulator. Driving under a strong glare condition may result in misestimated speed of a moving object. As we were able to show in previous studies (Huang et al., 2013), a mild glare-masking already reduced the performance in detecting the speed difference with the front vehicle. Discomfort glare may further affect the motion detection mechanism. Theeuwes et al. (2007) reported that car drivers chose a lower speed under discomfort glare condition. Pritchard et al. (2012) reported that drivers decreased their driving speed as a function of decreasing luminance in the simulated driving tasks. Drivers altered their driving speed relied on perceived target speed depending on the luminance level. In this study we

aimed to further investigate the effect of strong glare, i.e. achieving the luminance level of a direct sunlight higher than  $10000 \text{ cd/m}^2$ , on our speed detection performance. The experiment has been carried out in a driving simulator with an illumination system which enables high-level luminance driving environment. Participants performed a simulated driving scenario consisting of speed detection tasks with various speed settings of a front vehicle under glare and no-glare conditions.

## 2. Method

The speed detection experiment was run in a driving simulator. Each participant sat on a driver's seat and performed the task by watching test video projected on a  $3 \times 3 \text{ m}^2$  white projection wall in 3m distance. Two BarcoSIM5plus projectors (with SXGA resolution; aspect ratio 4:3; Field of View (H x V):  $49.12^\circ \times 37.85^\circ$ ) were used to provide identical/overlapped images for enhancing the contrast quality. Participants performed the task with the Logitech G25 driver's control interface. An illumination system (using one 200W incandescent lamp) was applied to enable high-level luminance driving environment. In the no-glare condition, the luminance of the target, i.e. the front car, was  $21.6 \text{ cd/m}^2$  with a background luminance of  $1.5 \text{ cd/m}^2$ . When the glare was present, which acted as a sun source in the periphery (center position to the eye: H, V:  $25.35^\circ$ ,  $10.77^\circ$  with a central luminance of  $28720 \text{ cd/m}^2$ ), the luminance of the visual target was  $22.7 \text{ cd/m}^2$  with a background luminance of  $2.6 \text{ cd/m}^2$ .

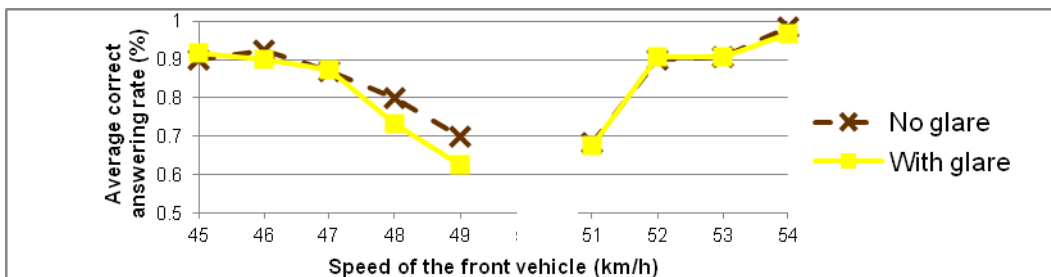
A simulated driving scenario consisting of a city road as the driving environment and a front vehicle superimposed on the background with various speed settings. Participants were asked to perform a two-alternative forced choice task which required them to report whether the speed of the front vehicle is slower or faster than their own speed. Responses were given by pressing two specified buttons on the steering wheel. Participants were made aware that the decisions should be given as fast as possible throughout the trials. The required reaction time for the speed detection task was recorded. The car speed of the participants was fixed at 50 km/h (speed limit in major city roads). The speed of the front vehicle was given randomly among the trials, varying from 45 to 54 km/h. The main experiment consisted of two blocks of a 10-minute video task, one block with no-glare applied and one with glare applied. In each block, there were 100 trials (10 of every speed setting of the front vehicle). In each trial (Fig. 1), the video started with a driving scenario with no vehicle ahead. After two seconds, a front vehicle was presented for the duration of 200 ms at the starting position of 13.89 m in front of the participant (corresponding to one-second traveling distance at the driving speed of 50 km/h). After 4 s from the beginning of each trial, a black frame was presented for two seconds for washing out the visual memory from the previous trial. Procedure: Before starting the task, participants were explained about the task content in the driving simulator and got adapted to the environmental set up, mostly the luminance level. A training session of two-minute was run before running the first block of the main experiment. After the training session, each participant performed two blocks of 10-minute speed detection task. 50% of the total participants started with the glare condition and the other 50% started with the no-glare condition.



**Figure 1** Template scenes of the test video: (a) each trial starts with a city driving scenario, (b) a front vehicle appears at various speed to be detected, (c) a black frame is shown to wash out the visual information between each trials.

### 3. Results

A total of 12 participants (2f, 10m) took part in this study. Under different speed settings of the front vehicle and two glare conditions (with glare / no glare), the average rates of correct answers are illustrated in Fig. 2. Besides, a two-Factorial ANOVA was run considering the two-level within-subjects factor of glare condition (no glare and with glare) and the nine-level within-subjects factor of speed condition ( $V_{\text{front vehicle}} = 45, 46, 47, 48, 49, 51, 52, 53, \text{ and } 54 \text{ km/h}$ ). Results showed a significant effect of speed condition ( $F(8, 88) = 12.126, p < 0.001, \text{ Effect size partial } \eta^2 = 0.524$ ). No significant effect of glare condition was shown ( $F(1, 11) = 3.085, p = 0.107, \text{ Effect size partial } \eta^2 = 0.219$ ). There was no significant interaction between the glare condition and speed condition ( $p=0.824$ ). Average reaction times were 920.6 ms in the no-glare condition and 907.8 ms in the glare condition. Average reaction time in the misestimated responses was 1153.9 ms (increased by 26.22% to the average of all).



**Figure 2** Results of mean correct answering rate vs. front vehicle speed under two glare conditions.

### 4. Discussion and Conclusions

Disability glare failed affecting significantly visual performance. This may be due to the experimental setup which enabled the drivers to shift their resources allocation to the speed discrimination task in the glare condition. The presence of glare probably kept drivers more alerted and focused cognitively during the test. As a result, such improvement could compensate for the reduced visual performance due to disability glare. This finding is not surprising as we were able to show in a previous study (in press), two mild-glare maskings affected the speed discrimination ability differently. The more distinct masking did not influence the speed discrimination by much since observers were better prepared and more concentrated on performing the task. This fact could play a role in the tunnel driving application. The masking effect near the entrance (highly-illuminated portal vs. dark interior) is likely a more important key factor than the strong disability glare for the safety concerns. We should provide the drivers a good overview of the interior situation when approaching the tunnel entrance, e.g. by improving tunnel lighting or by using in-car information systems.

### 5. Literature

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## Paper 2: Discomfort glare and speed discrimination

### Effect of Discomfort Glare on Speed Discrimination in a Simulated Driving Scenario

In: 20<sup>th</sup> ITS World Congress Tokyo 2013

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#### ABSTRACT

Good and stable driving skills, which highly rely on visual performance, are very important for traffic safety. Glare has been shown to have certain impacts on driving safety issues, such as driving in a low-sun condition or gazing into the headlamp of an oncoming vehicle. While disability glare causes reduced visibility of objects on the road which increases risky driving events, discomfort glare irritates visual perception and distracts visual attention which affects visual performance as well. In the present study, we investigate the potential effects of discomfort glare on motion perception. Participants performed speed discrimination tasks of a front vehicle with different speed set up in a simulated driving scenario under low-level luminance glare and no-glare conditions. Results showed that discomfort glare interfered in visual perception of motion and caused reduced detectability in speed discrimination. One should be aware of the misestimation of speed caused by discomfort glare when performing a driving task.

**Keywords:** Driving Skill, Visual Performance, Driving Safety, Discomfort Glare, Motion Perception, Speed Discrimination

#### 1. INTRODUCTION

Visual performance is one key factor of traffic safety in everyday driving tasks. When a car driver is exposed to various visual environments, certain visual functions may be affected and thus result in a risky driving event. For example, with the presence of high-level glare, i.e. the well-known "disability glare [1]," the road visibility is reduced as well as other objects on the road, e.g. the front vehicle, pedestrians, traffic signs, etc. Car drivers may receive an unclear overview and feel more difficult to perform continuing driving tasks when driving in such a disability glare environment. Menozzi et al. [2] reported a higher accident rate nearby the tunnel entrance on a highway based on a statistical analysis and revealed that the risk of accidents highly depended on the sun position. Critical situations happened when the sun acted as a direct glare source in the driver's central visual field or as an indirect glare source when the sun was reflected on the surface of the tunnel entrance to the car driver. Gray et al. [3] reported that in simulated low-sun conditions which caused reduced retinal image contrast, the safety margin, in terms of the time to collision (TTC) with approaching vehicles, was overestimated by the drivers while performing left-turn driving tasks in a simulator. Driving under a glare condition may result in misestimated speed of moving objects. Disability glare plays an

important role in traffic safety issues while affecting light adaptation mechanism of the drivers' eyes, and furthermore, may affect the motion perception mechanism.

Different from disability glare, when a car driver encounters a low-level luminance glare condition, the low-glare may cause visual discomfort without necessarily reducing visibilities of objects on the road and/or affecting the light adaptation of the eye. This is another common type of glare, the discomfort glare- a subjective sensation of discomfort. The International Commission on Illumination, CIE, considers discomfort glare of lighting by rating the visual environment with the UGR (Unified Glare Rating) formula [4]. Discomfort glare may interfere with cognitive functions, such as disturbing visual attention and perception, and further affect visual performance even though the effect of discomfort glare on light adaptation could be neglected. Many studies considering influences of discomfort glare have been carried out over the past few decades, however, they are mainly discussing for the office-work environments. People could suffer from discomfort glare in everyday driving tasks as well. In previous studies, we were able to show that a mild sort of glare resulted in reduced peripheral attention in a driving simulator [5]. Discomfort glare affected detecting and processing of visual information in the attention task. Especially attention and in particular peripheral attention have been identified as a predominant factor directly related to driving skills [6], therefore discomfort glare could be a major concern in driving safety issues. Theeuwes et al. [7] reported that one's actual driving behavior was affected by discomfort glare. For example, car drivers chose a lower speed under discomfort glare condition. Besides, a significant drop in detecting pedestrians on sidewalk was found in their study. In a more recent study, Pritchard et al. investigated the effect of luminance on simulated driving speed [8]. They reported that drivers decreased their driving speed as a function of decreasing luminance. In the simulated driving tasks, drivers altered their driving speed relied on perceived target speed.

We therefore ask: does discomfort glare affect car drivers' motion perception of a moving object on the road? The potential effects could result in severe situations since we have moving vehicles, walking pedestrians, etc. on the road. Besides, when driving towards a tunnel as abovementioned, what are the main causes of the traffic accidents? Inattentiveness while entering the tunnel has been considered as one of the most important causes resulting in the crashes into the front vehicle. Does the misjudgment of speed detection play a major role in addition to impaired vision caused by disability glare, or when there is no disability glare existed? As a result, we are particularly interested in knowing that whether discomfort glare may affect estimation of the speed of a front vehicle.

In the present study, the speed discrimination experiment was carried out in a driving simulator. In a simulated driving scenario, participants performed the video-based task. A front vehicle with different speed set up (faster or slower than the driver) was shown to the participant under different glare conditions (with discomfort glare or without glare). Participants were asked to estimate for the perceived speed of a front car, and to report if the front vehicle is driven at a higher speed or a lower speed in comparison with his/her own driving speed. We therefore investigated the possible influences of discomfort glare on one's motion perception of cognitive functions separately from effects of disability glare on visual performance of physiological functions.

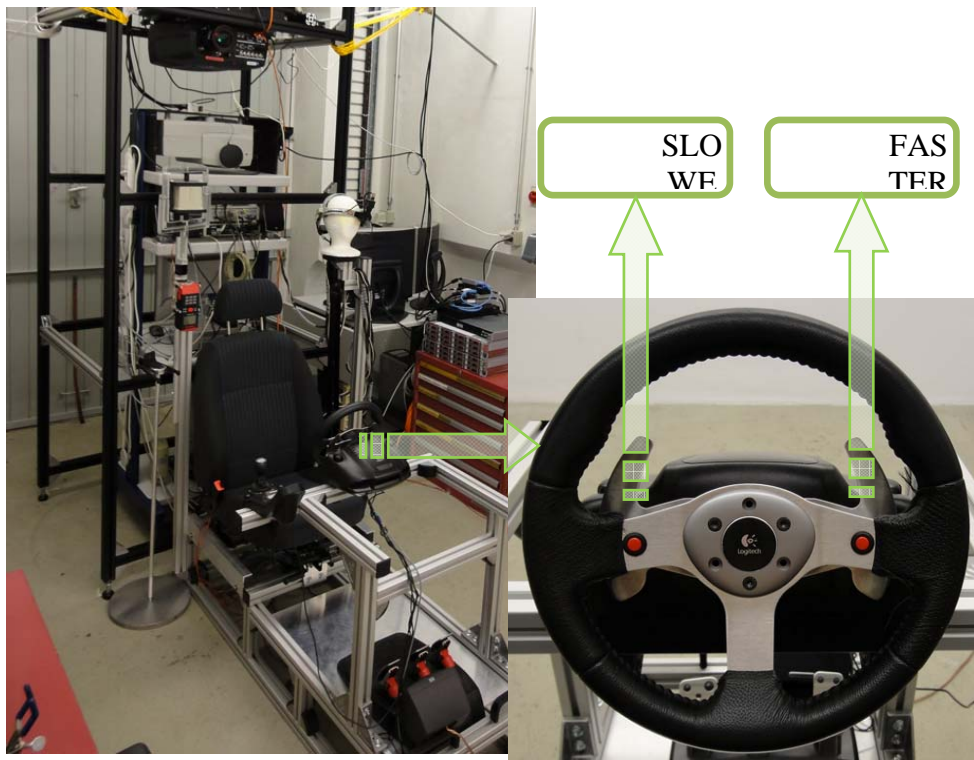
## 2. METHODS

### 2.1 Participants

A total of thirteen participants (three females and ten males) participated in the study. All participants had normal or corrected-to-normal visual acuity, and none of them had self-reported eye diseases. Two of the participants were the authors who were not aware of the test trial sequence of the experiment and the other eleven participants were naïve to the purposes of the study.

## 2.2 Instrumentation

The speed discrimination experiment was run in a driving simulator in virtual reality (VR), as shown in Figure 1. Participants sat on a driver's seat and performed the experiment by watching test videos and answering the tasks in a quiet garage environment. The BarcoSIM5plus projector (with SXGA resolution: 1400 x 1050; aspect ratio 4:3; Field of View (H x V): 49.12° x 37.85°) was used to display the test video on a 3m x 3m white projection wall at a distance of 3-meter to the participant. Participants performed the visual tasks with the driver's control interface (Logitech G25, steering wheel with position sensor, gas & brake pedal sensors, and other switches sensors). A control & record system (digitec Tharsis T90.19) with video scenario building tools, measurement recording tools using NI hardware and LabVIEW, was connected to both the projection system and the driver's control interface. Output data of the driver's control interface was sent to and recorded by a LabVIEW program for later analytical work. Luminance was measured using the Konica Minolta Luminance Meter LS-100.



**Figure 1** The driving simulator and the steering wheel used for responding the task.

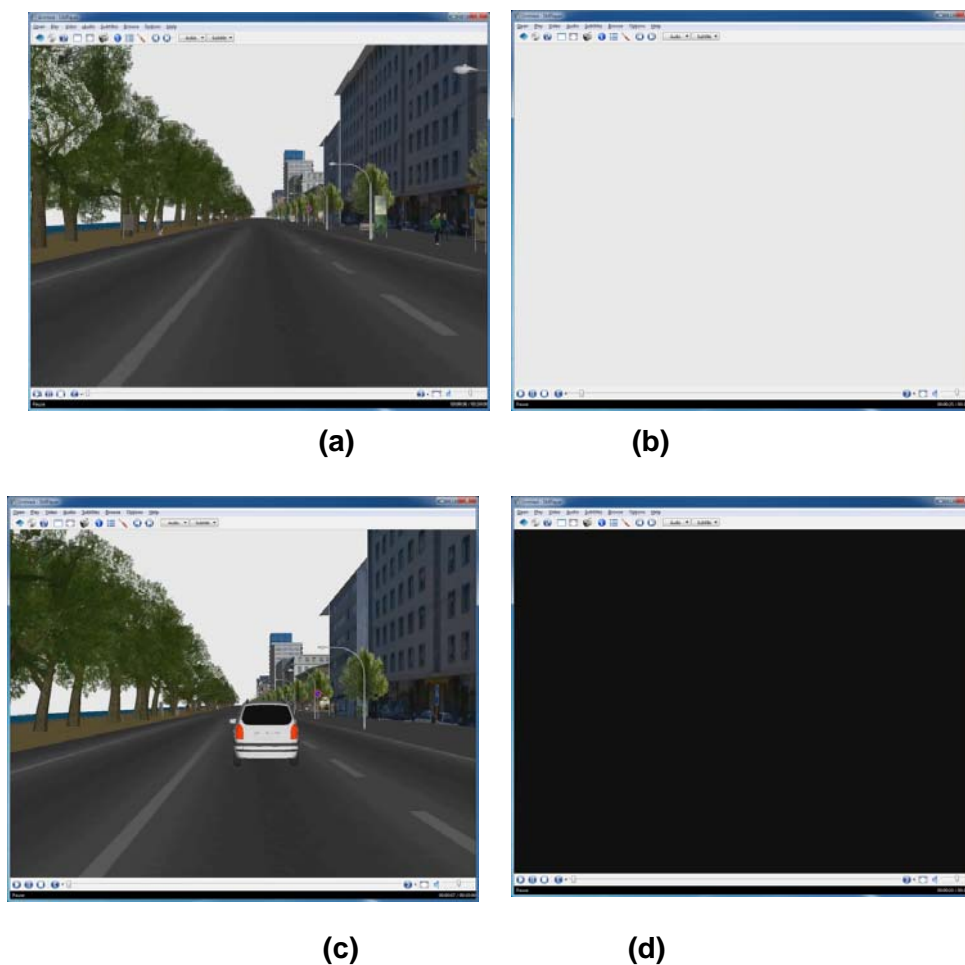
## 2.3 Experimental Design

Participants were asked to detect the speed of a front vehicle superimposed on a test video of a simulated driving scenario, which presented a city scene with a straight road. In a two alternative forced choice task, participants reported whether the perceived speed of a front vehicle was faster or slower in comparison with his/her own driving speed. The answers were given by pressing two specified buttons on the steering wheel (as shown in Figure 1). The car speed of the participants was fixed at 50 km per hour, corresponding to a common speed limit in many major city roads. The speed of the front vehicle was given pseudo-randomly among the total trials, varying from 45 km per hour to 54 km per hour.

The main experiment consisted of two blocks of a 10-minute test video. In each block, there were 100 trials. In each trial, the video started with a driving scenario with no vehicle ahead (with an average luminance of  $\sim 8$  cd/m<sup>2</sup> when fixating at the screen center close to the road end). After two seconds, depending on the set up of glare conditions, a flash of a blank frame in white color (RGB = 255/255/255) was applied or

not for the duration of 200 ms. Next, the stimulus, a front vehicle, was presented for the duration of 200 ms at the starting position of 13.89 m in front of the participant, which corresponded to one-second traveling distance at the driving speed of 50 km per hour. The luminance of the front vehicle, when gazing on the car, was  $\sim 12 \text{ cd/m}^2$ . After four seconds from the beginning of each trial, a black frame (RGB = 0/0/0) was presented for two seconds, which was used to wash out the visual memory from previous trial.

The white frame was used as a discomfort glare scene with a luminance of  $16 \text{ cd/m}^2$ . In 50% of the trials (out of a total of 200 trials for each participant), discomfort glare was applied prior to the presentation of the front vehicle. The sequence of trials with glare and without glare alternated pseudo-randomly. Figure 2 demonstrates template scenes presented to the participants in the experiment.



**Figure 2** Template scenes of the test video: (a) a trial starts with a city driving scenario, (b) a blank white frame used as a transient discomfort glare condition, (c) the stimulus- a front vehicle appears, (d) a black frame used to wash out the visual information between each trials.

## 2.4 Procedure

Firstly participants were explained about the task content in the driving simulator; meanwhile, participants were getting adapted to the environmental set up, mostly the low luminance level. Before running the first block of the main experiment, a training session of one-minute long was run for guiding participants the procedure of performing the task. Participants were instructed to report the answers by pressing the corresponding button on the steering wheel. After the training session, each participant performed two blocks of 10-minute visual task. Between the two blocks, participants took a short break.

## 2.5 Data analysis

From each participant, we got a total of 200 answers, 10 of each speed (10 different front vehicle speeds) and glare (with glare or without glare) combinations. Total data were collected and sorted into different subgroups (e.g. various speed of the front vehicle, correct/incorrect answers, and with/without glare conditions). Recorded data were analyzed in general mathematical/statistical methods.

Furthermore, we applied the theory of signal detection, a method for quantifying the ability of human beings for distinguishing a signal from a noise, for evaluating the experimental results [9]. While detecting the presence of a signal or not, we may come out with four different answers (as shown in Table 1): 1. “hit”- perceiving a signal with the presence of the signal; 2. “false alarm (FA)”- perceiving a signal with no presence of a signal; 3. “miss”- perceiving no signal with the presence of the signal; 4. “correct rejection (CR)”- perceiving no signal with no presence of a signal. In the present study, we defined the signal in two different situations: 1. when we evaluated for slower speed discrimination, the signal meant the speed of the front vehicle was slower than the participant (i.e. <50 km per hour); 2. For evaluating faster speed discrimination, the signal indicated a speed >50 km per hour.

**Table 1** Sender and receiver characteristics- from sender’s side, “Signal” and “No signal” represent that a stimulus exists or not; from receiver’s side, “Yes” and “No” mean that a participant observes a signal or not.

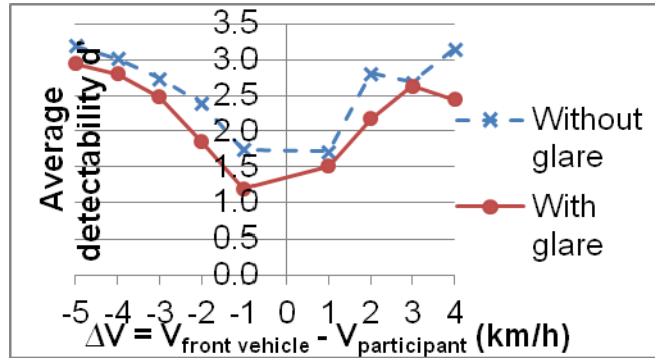
		Sender	
		Signal	No signal
Receiver	Signal	Hit	False alarm
	No signal	Miss	Correct rejection

## 3. RESULTS

We evaluated the recorded results of the total thirteen participants. Under different speed settings of the front vehicle and two glare conditions (with/without discomfort glare), the average rates of correct answers for each combination are shown in Table 2. Except the speed of 51 km/h and the speed of 53 km/h settings, for all the other speeds, the average correct answering rate is lower with the presence of discomfort glare. Experimental results among all participants were further analyzed based on the theory of signal detection. Detectability  $d'$  was used to evaluate the effects of discomfort glare, while a higher value of  $d'$  indicates better performance in the speed discrimination task. Figure 3 shows the mean detectability  $d'$  among different speed set up and the two glare conditions graphically. Results revealed that lower mean  $d'$  values were shown under the glare condition for all speed settings. The jnd (just-noticeable difference) increased with the presence of discomfort glare. Therefore, discomfort glare reduces the discrimination performance in speed detection. Besides, the asymmetric shapes of two curves (with and without applying glare) show the asymmetry in the jnd speed of the front vehicle under different glare conditions.

**Table 2** Average correct answering rate (%) among different speed settings and glare conditions (without and with glare).

	Speed of the front vehicle (km/h)								
	45	45	47	48	49	51	52	53	54
Without glare	96.15	92.31	89.06	81.54	66.15	65.38	89.23	88.46	96.15
With glare	93.08	90	84.44	70	50.77	70	81.54	92.31	88.21



**Figure 3** Graphical representation of the results of mean detectability  $d'$  vs. the speed difference ( $\Delta V$ ) between the participant and the front vehicle under two glare conditions.

Besides, a two-Factorial ANOVA was run considering the two-level within-subjects factor of glare condition (with glare and without glare) and the nine-level within-subjects factor of speed difference condition ( $\Delta V = -5, -4, -3, -2, -1, 1, 2, 3,$  and  $4$  km/h). Results showed a significant effect of glare condition ( $F(1, 12) = 8.021, p = 0.015,$  Effect size partial  $\eta^2 = 0.401,$  Observed Power =  $0.739$ ). As well as a significant effect of speed difference condition ( $F(8, 96) = 18.428, p < 0.000,$  Effect size partial  $\eta^2 = 0.606,$  Observed Power =  $1.000$ ) was shown. There was no significant interaction between the glare condition and speed difference condition ( $p = 0.299$ ).

#### 4. DISCUSSION

In the present study, we conducted the speed discrimination experiment in a driving simulator. Different from many other simple designs for laboratory experimental settings, we provided a simulated city-scenario as the video background since driving performance is affected by familiarity and the lifelike experience of a car driver. Note that the applied discomfort glare was supposed to stand at a low-level luminance without affecting the light adaptation of the eye. In other words, the potential effects caused by the glare set up in this study would be affected by cognitive functions but not the physiological visual functions. The results reveal that discomfort glare reduces the detectability in judging the front vehicle speed, as we have expected. The perceived speed of a moving object is misestimated caused by the presence of discomfort glare. This effect may be partially explained by the distraction and reduced attention resources caused by discomfort glare in general [5].

When we have a closer examination of the results shown in Figure 3, we may find that the turning points of the two curves occur at the opposite directions of speed difference, i.e. faster and slower front vehicle speed. In the glare condition, participants performed the tasks worst when the front vehicle was 1 km/h slower than his/her own speed; when the glare was not applied, the worst performance happened when the front vehicle was 1 km/h faster than the participants. In the experiment participants were driving at a fixed speed (50 km/h), in other words, participants received a constant optical flow of the visual background. As a result, the perceived speed of a moving object may be slower than its actual speed due to the effect of optical flow, which could fit the observations found in the no glare condition, as a controlled condition. However, in the glare condition, the optical flow of the background was shortly eliminated by the blank frame, which might help

participants to estimate the speed of the front vehicle more accurately. This might be a reason why the turning point was shifted to the left side (slower speed) with the presence of discomfort glare.

Moreover, we may notice that a more flat U-shape curve was shown in the glare condition. Let us take a mean  $d'$  value of 2.5 as a detection threshold, which represents a moderate discrimination task. With the presence of glare, participants were not able to achieve the  $d'$  threshold for a wider range of speed difference: the upper limit ( $\Delta V \approx +3$  km/h) and the lower limit ( $\Delta V \approx -3$  km/h) made a speed difference range of almost 6 km/h. When no glare was applied, a smaller range of speed difference below the  $d'$  threshold was shown: the upper limit ( $\Delta V < +2$  km/h) and the lower limit ( $\Delta V \approx -2$  km/h) made a speed difference range of less than 4 km/h. These observations might further indicate that discomfort glare interferes the motion perception mechanism.

In the present study, we have discovered certain important issues caused by discomfort glare in addition to the well-known adaptation problem of the eye. People should become more aware of how discomfort glare may affect our daily driving tasks. The speed discrimination of a front vehicle is affected by discomfort glare, which means that a severe impact on traffic safety is caused. For example, when driving toward a tunnel entrance is exactly a critical situation which strongly combines the “adaptation issue” (the physiology concern) and the “motion perception issue” (the cognition concern) at the same time. The layout designs of tunnels, especially for the entrance area, should be highly concerned about the influences caused by discomfort glare. Besides, with the increasing development of intelligent vehicles and advanced driver assistance systems (ADAS), we should consider implementing some discomfort glare detecting features in order to keep car drivers aware of risky events and avoid traffic accidents. We highly recommend setting up some proper regulations regarding the discomfort glare effects for the car drivers.

## 5. CONCLUSIONS

The effects of discomfort glare on speed discrimination were examined in a simulated driving scenario. Results reveal that discomfort glare reduces the performance in estimating the perceived speed of the front vehicle. Discomfort glare may further affect the motion detection mechanism. This could be of major importance in driving safety in addition to effects caused by a disturbed light adaptation of the eye. Both issues should be treated carefully.

## 6. ACKNOWLEDGMENTS

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## **Paper 3: Discomfort glare and peripheral visual information**

### **Effects of discomfort glare on performance in attending peripheral visual information in displays**

**In: Paper submitted and under revision in “Displays” (2014):**

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#### **Abstract**

Nowadays, large screens have become more and more popular. Therefore, the amount of information presented in the peripheral visual field has gained importance in many tasks at visual display units. Users of displays are often exposed to some change or difference in luminance in or between different areas of a display, which in turn may produce a phenomenon known as discomfort glare. Discomfort glare is likely to affect cognitive performance. The performance in the visual periphery is more susceptible to disturbances as is the case for the performance in the central visual field.

In order to examine the aforementioned issue, this study explored the effects of discomfort glare on detecting and processing peripheral visual information in a complex visual task. The task consisted of detecting the orientation of arrows presented in the central visual field and at 18° in the periphery. The arrows were superimposed on a background video and presented by a projection system in virtual reality. 50% of the presentations were preceded by a mild glare scene with a luminance of 25 cd/m<sup>2</sup> flashed prior to the stimulus. Experimental results of 56 participants were analyzed using the theory of signal detection. A significant difference (two-tailed t-test  $p = 0.01$ ) in detectability of stimuli ( $d'_{\text{glare}} = 1.87$ ;  $d'_{\text{no glare}} = 2.11$ ;  $\Delta d' = 0.24$ ) was obtained. Results show that discomfort glare impairs peripheral visual attention in a virtual reality environment. We therefore propose to consider discomfort glare as a factor affecting performance in detecting peripheral visual information. Discomfort glare should be included as a quality criterion in rating visual information, as for instance is done in present standards of displays, lighting, etc.

#### **Keywords**

Large displays; Peripheral visual field; Peripheral vision; Discomfort glare; Visual attention; Complex visual information

## 1. Introduction

In our everyday life, many times we cannot overcome the difficulties caused by a sudden glare situation when performing visual tasks. Glare has been considered as an important key factor which affects one's visual performance. The more well-known "disability glare" [1] has been discussed and investigated widely and frequently in many popular topics, such as the studies for safety-related research in car-driving [2, 3, 4, 5, 6], the light-adaptation mechanism in physiology-concerning discipline [7, 8], and so on. Disability glare disables the visual system to some extent and causes reduced visibility and contrast sensitivity. And this disabling may be caused by light scattered in the eye physiologically. A common example is when one drives at night and an oncoming vehicle with very bright headlights is approaching. Another more well-known form of glare is "adaptation glare" [1] occurring when the visual system is exposed to a sudden change in luminance. As the visual system requires some time to adjust its sensitivity to altered level of light, adaptation glare causes a temporary impaired vision.

People may know that disability and adaptation glare could be severe risk factors in visual tasks. However, many people are not aware of "discomfort glare" [1] which might irritate one's vision in addition to disability and adaptation glare [9]. Discomfort glare, a subjective sensation of discomfort, may occur when people do not necessarily notice any effect on their work performance [10], but people might complain about certain symptoms, such as eye discomfort, headache, etc., and reduce the work efficiency and quality. By means of an intervention study in Swedish mail sorting facilities, Hemphälä and Eklund [11] were able to show a significant reduction of eye discomfort after lighting conditions were improved and sources of discomfort glare were reduced. Based on the outcome of their study [11], the authors estimated that a total of 62'000 hours of sorting time per year could be saved by applying the improvements of their intervention study in all Swedish mail sorting facilities. In an office work environment, in particular with the usage of computer displays, the daylight through the window and the lighting system indoors often cause the phenomenon of discomfort glare and have been considered as a common problem [10, 12], in everyday life. For example, one may perceive lower luminance on the computer display where the main task is usually located, compared with the higher illuminated surrounding of the computer display [13]. Studies have been made to investigate the preference and postural symptoms of an office worker under different illuminating conditions for improving later on lighting and office designs [10, 12, 13, 14]. Furthermore, suggestions have been made to evaluate a sufficient objective and quantifiable rating index/method linked to the subjective phenomena for better understanding and predicting potential discomfort glare problems which is still a challenge to be achieved [5, 10].

Discomfort glare causes visual distraction, and/or vice versa [15]. It is our cognitive mechanisms which decides how to proceed with our visual attention when exposed to discomfort glare which acts as a distracter. As a result, while causing visual discomfort, discomfort glare is also sharing our perception resources which affects our visual attention in the cognitive level.

In many times we are not well-prepared for the possible effects on our visual attention caused by discomfort glare situation, which is happening even more frequently in our routine works. For example, when we work on our computers, a newly-opened web-browser window might distract our visual attention for a short while. Or in the training-stage with a flight simulator, how would the pilot be disturbed by the discomfort glare in a simulated task? A control-room administrator might have some difficulties in making decisions when encountering the reflection of a bright object on the screens. Moreover, for our leisure time entertainment, discomfort glare situations happen regularly as well. For example, we can easily find a bright scene from a video game such as applying a magic spell in a R.P.G. game, or a shining sky scene from a movie, etc. This kind of discomfort glare usually stands at a low level luminance compared to light levels causing disability and adaptation glare, and this happens to us with various display media almost every day. As a result, it is important to know how a situation causing discomfort glare would distract our visual attention from the required visual information.

Wickens et al. [16, 17] have developed an attention model, which may help to understand effects of discomfort glare on visual performance. The basic idea in Wickens' model is the limitation of resources which are available for information processing. Discomfort glare may bind resources therefore reducing the amount of available resources for processing visual information. As a consequence, performance in processing relevant information may be reduced in the presence of discomfort glare. Binding of resources caused by discomfort glare may happen for various reasons. First, the steady state visibility of visual information may be reduced by the overlay of discomfort glare therefore requiring a major effort for processing the information. In Wickens' SEEV model [16, 17], required effort contributes negatively to the probability for attending a target. Second, glare may temporarily mask the visual information and require a reprocessing period of the information after it becomes unmasked. A large variety of factors contributing to masking have been investigated in the past [18, 19]. As the masked visual information was usually of limited complexity, such as words [20] or simple objects, it is hard to use previous findings in order to predict effects of masking when using a complex display, which is usually presented in a simulator or in our daily lives.

The display in everyday life includes both relevant information and some information that is not used in a specific task and therefore is considered to be irrelevant. Irrelevant information acts as a distractor when performing a visual task. The process of neglecting irrelevant information while attending the relevant information may use resources as well, and consequently a complex display including irrelevant information lowers performance in attending the relevant information. As a result, it is important to investigate effects of discomfort glare while observing a complex display.

Nowadays, we have easy access to large-sized and wide-angle computer displays, LED/LCD-TV, and projection systems at work and at home. With the increasing usage of various displays which present visual information in a wide visual field in modern times, we may need to rely on our peripheral vision much more than in the past. As a result, how we perform our visual tasks when visual targets located in both our central and peripheral visual fields has become an important issue. Normally we tend to, or we are used to, focus on the visual information showed in the central visual field, especially when we have heavy load in our visual tasks. Thus, it might take us more efforts from the attention mechanism to detect peripheral information under a complex visual task.

Moreover, the age factor might play a role in performing visual tasks affected by discomfort glare. With increasing veiling luminance in the elderly, we might expect stronger effects in visual performance caused by discomfort glare for the elderly than the younger population.

In the present study, we investigated effects of discomfort glare on visual performance in a complex and temporarily varying visual environment. In particular, and since the peripheral visual field is of increasing interest for presenting information, we investigated effects of discomfort glare when both, the central and the peripheral vision are involved in a visual task. Effects were investigated using a projection display in a driving simulator task with participants of different ages.

## 2. Methods

### 2.1 Participants

Fifty-six participants, 26 females and 30 males, participated in the experiment. Participants ranged in age from 24 to 64 years, with the mean age of 41.14y and a median of 38y. None of the participants reported any ocular diseases. All had normal or corrected-to-normal vision as determined by the vision examinations. Participants wore their habitual optical correction for far vision during the experiment, if applied. The experiment consisted of one session of vision examination and one session of attention test in the driving simulator, in a total of 30 minutes, approximately. Participants were

recruited from the ETH Zurich and the University of Zurich campuses and were rewarded a small gift after completing the experiment.

The present study has been approved by the Research Ethics Committee of ETH Zurich. All participants were given a full explanation about the experimental procedures orally and in a written form. A consent form was obtained with the right to withdraw from the study at any time without giving reasons and without any negative consequences.

## 2.2 Vision Examination

The Rodatest 302 vision screening device (Rodenstock, Germany) was used to examine the far visual acuity (G25 test for right/left/binocular vision) and the peripheral vision (GESICHTSFELD test for right/left peripheral visual fields at 35, 55, 70, and 85 degrees). Besides, the AR-1000 AUTO-REFRACTOMETER (Nidek, Japan) was used to check the refractive error for both eyes with habitual optical correction, if applied. Finally, we used the LANG-STEREOTEST for disparities of 550", 600", and 1'200" to check the stereoscopic vision.

## 2.3 Attention Test

The visual attention experiment was run in a driving simulator in virtual reality. In this test, participants were asked to detect a particular feature in projected test videos and to report detected feature by operating the steering wheel on a driver's seat.

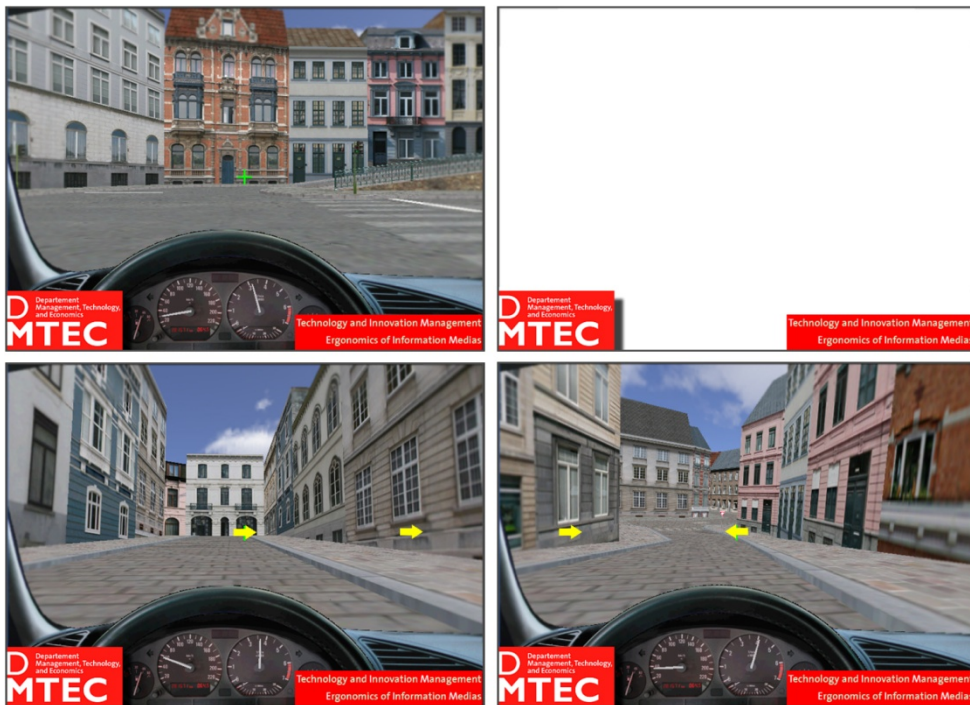
### 2.3.1 Instrumental set up

The test videos were displayed on a 3m by 3m white projection wall vertically by a projection system (BarcoSIM5plus, projector with SXGA resolution, aspect ratio of 4:3, and field of view (H x V) of 49.12° x 37.85°) at a distance of 3 meters to the observer. There was no auditory effect provided. Participants performed the visual tasks with the driver's control interface (Logitech G25, steering wheel with buttons & position sensors and accelerator & brake pedal sensors). To report their answers for the given tasks, they pressed two corresponding buttons on the steering wheel. The driver's control interface and the projection system were both connected to a control and record system (HP xw9400 workstation) which recorded the output signals of the driver's control interface, i.e. the answers, by a LabVIEW program. Recorded data were sent to an output log file simultaneously for later uses.

### 2.3.2 Experimental design

During the task, participants were asked to keep their fixation on a fixation cross which was centrally superimposed on a video of a simulated driving scenario. Immediately after the fixation cross disappeared a central and a peripheral arrow appeared superimposed on the video. Participants performed a two-alternative forced choice (2AFC) task which required them to report whether the orientations of two horizontal arrows are the same or opposite by pressing two specified buttons on the steering wheel. Fig. 1 shows template scenes of the video-based tasks. The main experiment consisted of four blocks of a two-minute test video. In each block, there were 20 trials of the arrows sets. The two arrows, with the same geometry, were both shown in yellow color (RGB = 255/255/0) and with the luminance of 15 cd/m<sup>2</sup>. The "central arrow" was presented centrally (0°) in the visual field and pointed either to the right direction or to the left direction. The "peripheral arrow" was presented at the same time at a periphery of 18° horizontally and located according to the

direction the central arrow was pointing. The peripheral arrow also pointed either to the right direction or to the left direction. Both arrows subtended a horizontal angle of  $140'$  (minutes of arc). The two arrows were displayed simultaneously and were visible for the duration of 400 ms for the central arrow and 200 ms for the peripheral arrow. The peripheral arrow was presented shorter than the central arrow for preventing fixation on the peripheral arrow. Following a review reported by Becker [21] the latency for a saccade to a target located at  $18^\circ$  in the periphery is about 200 ms and the duration of the saccade of an amplitude of  $18^\circ$  is about 52 ms. The duration settings were tested in a pilot experiment. Based on the experimental results of the pilot study, the final test was designed to be applicable yet not too easy for the general population.



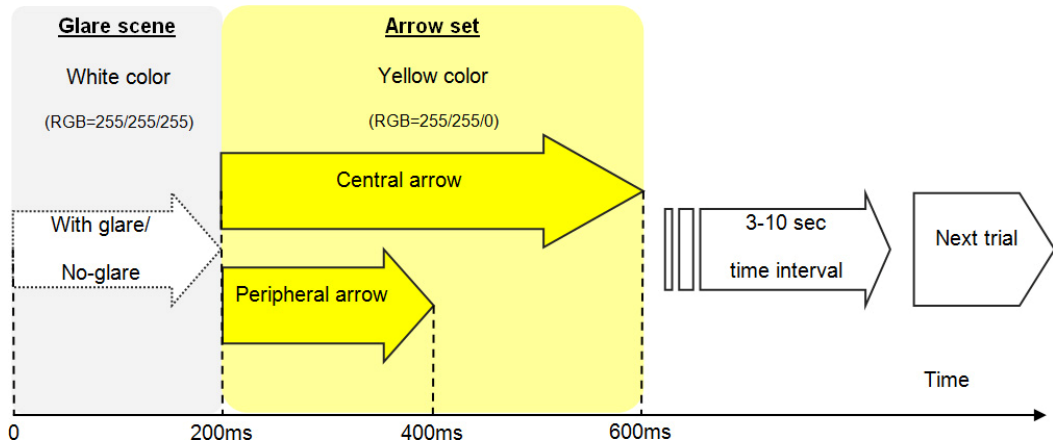
**Figure 1** Scenes template of the task. Upper left: the fixation cross when no arrows were shown; upper right: the mild glare scene generated by a blank frame; lower left: same orientations of one arrow set; lower right: different orientations of one arrow set.

In 50% of the trials, further on referred to as the “glare condition”, we applied a flash of a blank frame prior to the presentation of the arrow set. The blank frame, which was shown in white color (RGB = 255/255/255) with a luminance of  $25 \text{ cd/m}^2$ , was visible for the duration of 200 ms and generated a transient mild glare scene. The sequence of trials with glare and without glare alternated pseudo-randomly. Each participant performed 40 trials with and 40 trials without applying glare stimuli. Fig. 2 shows the sequence of the trial. Before running the first block of the main experiment, a one-minute training session was applied to instruct participants how to perform the task. This could also help the examiner to check if the participant has understood and performed the task correctly.

## 2.4 Data Analysis

From each participant, we got a total of 80 answers after running the four blocks of test videos. We used the theory of signal detection [22] to analyze the results. When one trial consisted of two arrows with the same orientations, this was defined as a signal. Depending on how participants detected the signals, they may generate “hits,” i.e. signals were detected, or “misses,” i.e. signals were not detected. And in the no signal cases, i.e. the arrow set consisted of opposite orientations, participants may generate “correct rejections” or “false alarms.” Total answers were collected and sorted into different data

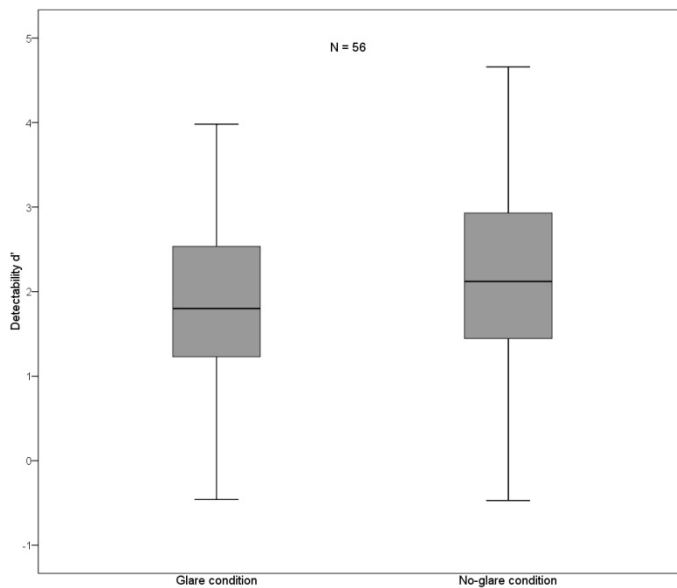
sets (e.g. glare condition) for further analysis. In particular, we used detectability  $d'$  to evaluate possible effects among various conditions.



**Figure 2** The stimuli sequence of the trials. The time interval between trials varies pseudo-randomly.

### 3. Results

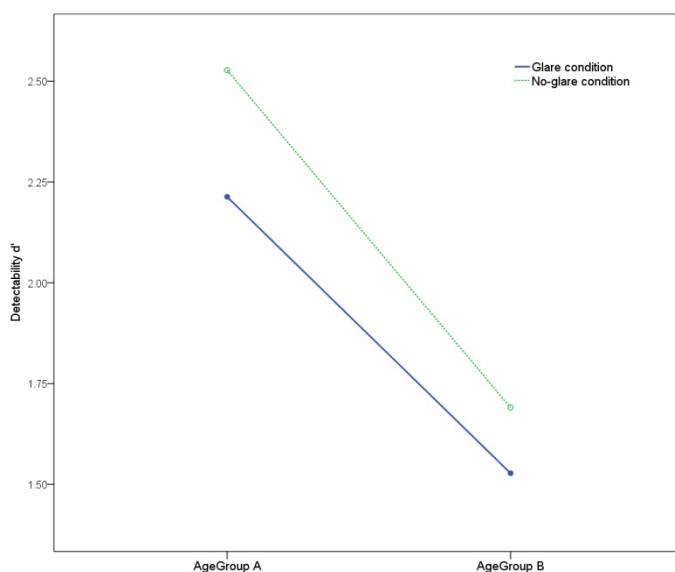
We evaluated the results of the total 56 participants. In the 40 trials with glare preceding the presentation of the two arrows, a mean correct rate, i.e.  $p(\text{Hit}) + p(\text{CR})$ , was 78.96% (SD = 11.72%). In the other 40 trials with no glare preceding the presentation of the two arrows, a mean correct rate was 80.68% (SD = 15.11%). Based on the theory of signal detection, the average detectability  $d'$  were 1.87 (SD = 0.94) in glare condition and 2.11 (SD = 1.19) in no-glare condition. Fig. 3 illustrates the results with a box-plot. Participants performed significantly better in detectability when no glare was applied (two-tailed t-test,  $t(55) = -2.614$ ,  $p = 0.012$ ).



**Figure 3** Box-plot diagram presenting the distribution of detectability  $d'$  in the glare condition and the no-glare condition of the total 56 participants.

In order to investigate the possible effect of the age factor, we divided the total participants into two age groups by a median split. AgeGroup A (24y to 36y) had 14 female and 14 male subjects with the mean age of 29.61y and the median of 29y. AgeGroup B (40y to 64y) had 12 female and 16 male subjects with the mean age of 52.68y and the median of 53y.

A 2x2 ANOVA was run considering the two-level within-subjects factor of glare condition (glare and no-glare) and the between-subjects factor of AgeGroup (AgeGroup A and AgeGroup B). Results showed a significant effect of glare condition ( $F(1,1) = 6.793$ ,  $p = 0.012$ , Effect size  $\eta^2 = 0.112$ , Power = 0.726). And a significant effect of AgeGroup ( $F(1,1) = 9.014$ ,  $p = 0.004$ , Effect size  $\eta^2 = 0.143$ , Power = 0.839) was shown as well. There was no significant interaction between the glare condition and the AgeGroup ( $p = 0.412$ ). Fig. 4 shows the mean detectability  $d'$  in different glare conditions of two age groups graphically. In AgeGroup A, mean  $d'$  were 2.21 (SD = 0.84) of the glare condition and 2.53 (SD = 0.91) of the no-glare condition. In AgeGroup B, mean  $d'$  were 1.53 (SD = 0.92) of glare condition and 1.69 (SD = 1.30) of the no-glare condition.



**Figure 4** Graphical representation of the mean detectability  $d'$  of AgeGroup A and AgeGroup B under different glare conditions.

#### 4. Discussion

In this study, video-based visual tasks were applied to participants with various ages. Those tasks contained a video background with moving objects and visual targets located both in the central visual field and in the periphery. In other words, participants detected visual signals and made decisions based on their central vision and peripheral vision as well in a complex visual environment. Under different conditions, i.e. visual tasks with and without applying transient discomfort glare scenes, detectability  $d'$  was used to investigate the possible effects on our visual performance. We have found out the detectability  $d'$  dropped in the discomfort glare condition among all participants.

An important question to answer is how far the recorded drop in performance might have been related to a loss of sensitivity caused by the varying level of light adaptation of the eye. Various studies have reported an increase in luminance threshold for detecting a visual target when the surround or the background of the target is briefly increased in luminance. Bichao et al. [23] investigated luminance threshold for detecting a disc

subtending  $11.4'$  and presented for 15 ms in duration either in the fovea or at an eccentricity of  $2.8^\circ$ . Compared to the dark adapted eye, luminance threshold in Biacho's experiment and for the foveal presented stimulus raised from about  $3 \text{ cd/m}^2$  for the dark adapted eye to about  $4.4 \text{ cd/m}^2$  when a glare of  $17.5 \text{ cd/m}^2$  surrounding the stimulus was applied. In the case a surrounding glare of  $70 \text{ cd/m}^2$  was applied, luminance threshold shifted to higher values depending on the asynchronicity between the onset of the glare and the onset of the stimulus. Presenting the stimulus 15 ms after glare onset raised the threshold to  $10 \text{ cd/m}^2$  whereas presenting the stimulus 500 ms after glare onset caused the threshold to increase to  $5 \text{ cd/m}^2$ . In average, the effects were stronger (about 30%, compare fig. 11 in [23]) in the periphery. As also noted by Crawford [24], luminance threshold peaked at about the time of the onset of the glare and then decreased with time. When the glare was switched off, threshold luminance peaked again; however, the peak at switch-off time of the glare was considerably lower than the peak at the onset of the glare. The peak in luminance threshold at switch-off time disappeared for a glare of about less than  $100 \text{ cd/m}^2$ . As can be learned from Crawford, threshold drops fast after switching off the glare, so that for low glare level conditions (about  $100 \text{ cd/m}^2$  in [24]), sensitivity reaches almost the sensitivity at dark adaptation level within around 100 ms. Compared to our settings, Bichao's results for the 500 ms stimulus onset asynchronicity with a glare of  $70 \text{ cd/m}^2$  caused a luminance threshold of about  $5.6 \text{ cd/m}^2$  (and about a 30% higher one in the periphery), can be used as a worst case estimation about the effect of transient adaptation on visual performance. Although we would have simultaneously surrounded the yellow target ( $15 \text{ cd/m}^2$ ) by the white frame ( $25 \text{ cd/m}^2$ ) in our experiment, the arrow would still have been visible. Moreover, since the luminance threshold rapidly drops further after the switch off, visibility of the arrow in our experiment is additionally improved as compared to Bichao's experiment. We therefore believe that it is unlikely that effects of transient adaptation would have affected visual performance in our experiment.

Significant effect on  $d'$  caused by discomfort glare was shown in all ages. We found out discomfort glare affected our visual performance in a complex visual task with the displayed media causing visual attention impairment in periphery. Discomfort glare might distract one's visual attention system thus one cannot focus on the visual information continuously. This finding here could be a major concern in our daily life. The glare scene applied in this study is generated by a blank frame in a projected medium to the observer, which represents a similar situation we might encounter when acquiring information from a display. According to Wickens' SEEV model [16, 17], the glare in this study may affect the "Expectancy" and the "Effort" parameters. It is quite likely that participants would expect an upcoming event (to detect the orientations of the arrow set) when a glare scene appears as a hint, i.e. the probability of attending the task should be increased. At the same time, the glare scene distracted participants and required them some extra efforts to recall their visual memories to perform the visual task continuously, i.e. reduced visual attention could be expected. From the result we have found, we may assume that the influence on "Effort" is larger than on "Expectancy" caused by discomfort glare in the experimental set up. Moreover, if our experimental set up was such as not to generate an increased expectancy, the effect of discomfort glare on visual performance would have turned out even stronger.

Regarding the age factor, we found out with increasing ages, the detectability decreased in both the glare and the no-glare conditions, i.e. in general elder people might need more time for processing visual information than younger people. However, there is no correlation between the age factor and the drop of  $d'$ , which means discomfort glare results in same effects in all ages. It seems to be no influence of the veiling luminance.

In present standards and specifications, we may find some guides, restrictions, or design requirements which consider for a disability glare situation, i.e. nature sun light. However, a mild glare situation, and in general discomfort glare, should be considered as a criterion in present standards of displays, lighting, etc. as well.

## 5. Conclusions

In a projection environment, participants performed attention tasks which contained complex visual information and required them to detect visual targets relied on both the central vision and the peripheral vision. Results showed reduced visual performance in all ages when transient discomfort glare was presented. Discomfort glare reduces performance in detecting or processing peripheral information and therefore should be avoided.

When exposed to a sudden discomfort glare situation which acts as a distracter, one's limited resource for processing visual information is shared. As a result, it is quite likely one may miss some important visual information in such a case. This might result in crucial issues when one is performing visual inspections of switching information for safety and quality control at airports or power plants, or for examination in hospitals or factories, etc. Also, with the development of electronic paper technologies, there are more and more e-paper devices introduced in our daily life, e.g. e-books, with the low refresh rate of the displayed information. We should be aware of the possible effects and to think about how to improve our decision-making mechanisms. Where to present and how to arrange various visual information on a display is an important issue then. For example, we should avoid any distracting factor while performing a critical visual task and the most important information should be displayed in the central visual field.

Finally, the experimental outcome demonstrates that display systems, as used in virtual reality settings, offer the possibility to conduct experiments about effects of glare on human performance even though the luminance level of such display systems is far lower than the luminance level of real glare source.

## Acknowledgments

This work was supported in part by the Swiss federal road administration ASTRA (Project No. FGU2010/003). The authors thank the volunteers for participating in the pilot test as well as Esther Baumer-Bergande for her great help in advising and running the vision examination.

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# Projektabschluss



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## FORSCHUNG IM STRASSENWESEN DES UVEK

Version vom 09.10.2013

### Formular Nr. 3: Projektabschluss

erstellt / geändert am: 04.07.2014

#### Grunddaten

Projekt-Nr.: FGU 2010/003

Projekttitel: Fehlschätzung der Kollisionszeit bei der Tunneleinfahrt bedingt durch eine gestörte Adaptation

Enddatum: 14.10.2013

#### Texte

Zusammenfassung der Projektergebnisse:

Der Sonnenstand ist ein Risikofaktor! Dies folgt aus einer statistischen Analyse von Verkehrsunfällen, die sich in der Nähe der beiden Portale des Gubristunnels ereignet haben. Auf die Portale des Gubristunnels zufahrende Autofahrer und Autofahrerinnen sind einem erhöhten Unfallrisiko ausgesetzt, wenn sie die Sonne knapp über der Portalwand sehen können. Ebenso ist für diese Autofahrerinnen und Autofahrer das Unfallrisiko erhöht, wenn sie durch Spiegelreflexion des Sonnenlichtes an der Portalwand geblendet werden können. Um das Unfallrisiko möglichst gering zu halten, sollten der Sonnengang, Reflexionseigenschaften, Orientierung und Form der Portalwand bei der Planung berücksichtigt werden. Bauliche Massnahmen zur Abschattung der Sonne können ebenfalls berücksichtigt werden. Im Falle des Gubristunnels wären diese mit hohem Aufwand verbunden.

Um den Beitrag der Blendung am oben genannten Unfallrisiko zu untersuchen, wurden vier Laborexperimente durchgeführt. Die Experimente wurden so konzipiert, dass sie vor allem Erkenntnisse zu den bei Portalen häufig auftretenden Auffahrnfällen liefern sollen.

Ein erstes, in unserem Fahrsimulator durchgeführtes Experiment, zeigte überraschenderweise, dass eine starke ( $28720 \text{ cd/m}^2$ ), in der Nähe des Blickes gerade aus ( $28^\circ$  im peripheren Gesichtsfeld) montierte Blendquelle, nicht notwendigerweise die Fähigkeit mindert, die Geschwindigkeit eines voranfahrenden Fahrzeuges richtig einzuschätzen. Die Resultate des Experimentes lassen vermuten, dass nebst der Blendung, auch andere Faktoren zum Unfallrisiko beitragen, wie z. B., die beim Tunneleintritt sich schnell ändernden Inhalte der visuellen Umgebung.

In einem zweiten Experiment wurde untersucht, wie sich der schnell ändernde Inhalt einer visuellen Umgebung auf das Vermögen Geschwindigkeiten zu schätzen, auswirkt. Die Resultate des zweiten Experimentes zeigen, dass die Schätzung der Geschwindigkeit eines voranfahrenden Fahrzeuges ungenauer wird, wenn kurz vor Durchführung der Schätzung, die Fahrscene während einer kurzen Dauer (20ms – 200ms) durch ein weisses Bild abgedeckt wird. Da die Leuchtdichte des weissen Bildes in etwa gleich der mittleren Leuchtdichte der Fahrscene eingestellt wurde, ist davon auszugehen, dass der gefundene Effekt nicht auf die Störung der Lichtadaptation des Auges zurückzuführen ist. Die zunehmende Ungenauigkeit bei der Geschwindigkeitsschätzung könnte durch die Zunahme der mentalen Belastung bedingt sein, die durch die Verarbeitung der sich schnell ändernden, visuellen Umgebung entsteht. Somit würden auch Effekte der mentalen Belastung zum Unfallrisiko bei der Tunneleinfahrt beitragen. Um die mentale Belastung bei der Tunneleinfahrt zu minimieren, sollten die visuellen Umgebungen vor und im Tunnel möglichst einander angeglichen werden. Bei guter Sichtbarkeit des Tunnelinneren, könnten die herannahenden Autofahrerinnen und Autofahrer bereits vor Tunneleintritt mit der Verarbeitung der visuellen Umgebung beginnen, wodurch eine akut hohe mentale Belastung vermieden werden könnte. Eine gute Beleuchtung der Einsichtstrecke (z. T. auch Einfahrtsstrecke genannt, ist die Strecke mit der Länge des Anhalteweges und die am Tunneleingang beginnt) ist wichtig! Die mentale Belastung liesse sich auch durch Verwendung von Fahrassistenzsystemen optimieren, mit denen eine Vorabinformation über das Tunnelinnere gegeben werden könnte.

In einem dritten Experiment konnte nachgewiesen werden, dass eine schnelle Änderung der Inhalte der visuellen Umgebung auch in der visuellen Peripherie zu einer Leistungseinbusse führt. Die Leistungseinbusse ist erheblich und vergleichbar mit der Leistungseinbusse, die durch eine Blutalkoholkonzentration von 0.2 0/00 bis 0.5 0/00 erzeugt werden kann. Oben erwähnte Massnahmen zur Verhinderung der Leistungseinbusse durch schnell variierende Inhalte der visuellen Umgebung lassen sich auch zur Verhinderung der Leistungseinbusse im peripheren Gesichtsfeld anwenden.

Die Autofahrerin bzw. der Autofahrer sieht die visuelle Umgebung als bewegt. Diese Bewegung erzeugt auf der Netzhaut einen sogenannten optischen Fluss. Der optische Fluss kann wesentlich zur Güte beitragen, mit der eine Fahraufgabe gelöst wird. Eine Änderung in der visuellen Umgebung, z.B. beim Einfahren in den Tunnel, erzeugt eine Änderung des optischen Flusses, was sich wiederum auf die oben erwähnte Güte auswirkt. Somit könnte die durch die Tunneleinfahrt bedingte Änderung des optischen Flusses ein zusätzlicher Risikofaktor für Unfälle an Tunnelportalen sein. Zur Überprüfung dieser Annahme könnte die Änderung im optischen Fluss bei der Einfahrt bestehender Tunnels untersucht und mit den entsprechenden Unfallraten an Tunnelportalen korreliert werden. Hierzu müsste eine Methode entwickelt werden, um den optischen Fluss aussagekräftig zu quantifizieren. Als Beispiel einer möglichen Methode wird hier die Analyse mittels Spektrogramm (zeitlicher Verlauf des Fourierspektrums) vorgestellt.

An sonnigen Tagen kann bei der Einfahrt in den Tunnel die Lichtadaptation des Auges stark gefordert sein, da sich das Auge rasch an grosse Unterschiede des Lichtniveaus anpassen muss. Die Sichtbarkeit hängt u.a. vom kurzzeitigen ( $< 2 \text{ s}$ ) Verlauf der Lichtadaptation (transiente Adaptation) ab. Gemäss den Resultaten unseres vierten Experimentes müsste der Leuchtdichtekontrast (Weber-Kontrast) von Objekten in der Einsichtzone um das Fünf- bis Zehnfache erhöht werden, damit Objekte in der Einsichtzone vergleichbar sichtbar werden, wie die Objekte vor der Tunneleinfahrt. Übereinstimmend mit Resultaten anderer Forschung, konnten wir nachweisen, dass eine Erhöhung des Lichtniveaus des Objektuntergrundes signifikant die Sichtbarkeit der Objekte verbessert. Unser Experiment wurde unter vergleichbaren Lichtverhältnissen durchgeführt, wie sie beim Uetlibergtunnel an einem sonnigen, wolkenlosen Tag gemessen worden sind (hier nicht wiedergegeben). Die Ergebnisse sprechen dafür, dass eine Erhöhung der Tunnelbeleuchtung in der Einsichtzone die Sichtbarkeit verbessert und somit zur Reduktion des Unfallrisikos beiträgt.



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#### Zielerreichung:

Der Effekt der Blendung auf das Unfallrisiko bei der Tunneleinfahrt konnte nachgewiesen werden. Darüber hinaus konnte gezeigt werden, dass zusätzlich zur Störung der Lichtadaptation des Auges, die Änderung der visuellen Umgebung das Unfallrisiko zu erhöhen vermag. Diverse Massnahmen zur Risikoreduktion werden vorgeschlagen. Unter anderem wird dringend empfohlen, in Bezug auf die Blendung kritische Abschnitte im Schweizer Strassennetz zu identifizieren als auch bei der Planung von Tunnelportalen den Sonnengang, Reflexionseigenschaft und Orientierung des Portals zu berücksichtigen. Auch wird empfohlen, bestehende Normen der Tunnelbeleuchtung kritisch zu überdenken.

#### Folgerungen und Empfehlungen:

Um das Unfallrisiko möglichst gering zu halten, sollten der Sonnengang, Reflexionseigenschaften, Orientierung und Form der Portalwand bei der Planung berücksichtigt werden. Bauliche Massnahmen zur Abschattung der Sonne können ebenfalls berücksichtigt werden. Um die mentale Belastung bei der Tunneleinfahrt zu minimieren, sollten die visuellen Umgebungen vor und im Tunnel möglichst einander angeglichen werden. Die mentale Belastung liesse sich auch durch Verwendung von Fahrassistenzsystemen optimieren, mit denen eine Vorabinformation über das Tunnelinnere gegeben werden könnte. Der Leuchtdichtekontrast (Weber-Kontrast) von Objekten in der Einsichtzone müsste um das Fünf- bis Zehnfache erhöht werden, damit Objekte in der Einsichtzone vergleichbar sichtbar werden, wie die Objekte vor der Tunneleinfahrt. Eine Erhöhung des Lichtniveaus des Objektuntergrundes verbessert signifikant die Sichtbarkeit der Objekte. Eine Erhöhung der Tunnelbeleuchtung in der Einsichtzone könnte somit zur Reduktion des Unfallrisikos beitragen.

#### Publikationen:

- 1) Menozzi M, Mauch D, Huang YY, Neracher M, Tunnel lighting: The role of environmental factors in high-way traffic accidents in proximity of tunnel entrances, GfA-Press, Dortmund, 2013
- 2) Huang YY, Menozzi M, Effect of strong glare exposure on speed detection task in a simulated driving scenario, GfA Press suppl., Dortmund, 2014
- 3) Huang YY, Menozzi M, Effect of Discomfort Glare on Speed Discrimination in A Simulated Driving Scenario, 20th ITS World Congress Tokyo, 2013
- 4) Huang YY, Menozzi M, Discomfort glare and peripheral visual information Effects of discomfort glare on performance in attending peripheral visual information in displays, Dispalys (submitted and under revision, 2014)
- 5) Huang YY, Menozzi M, Transient light adaptation as appearing when entering a tunnel at a sunny day. (in preparation)

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## FORSCHUNG IM STRASSENWESEN DES UVEK

### Formular Nr. 3: Projektabschluss

#### Beurteilung der Begleitkommission:

Beurteilung:

Die Projektziele wurden erreicht indem die Hypothese experimentell bestätigte, dass abrupt ändernde Lichtbedingungen im Portalbereich sowie Änderungen in der visuellen Umgebung zu einer Fehlbeurteilung der Kollisionsgefahr führen. Ferner wurden Empfehlungen für die Praxis formuliert.

Umsetzung:

Die Forschungsergebnisse und die sich daraus ergebenden Empfehlungen für die Praxis werden im Rahmen von wissenschaftlichen Veröffentlichungen verbreitet.

weitergehender Forschungsbedarf:

In der Arbeit wird der Fall des Gubristunnels detailliert analysiert. Eine Erweiterung der empirischen Basis durch weitere ausgewählte Bauwerke erscheint dringend erforderlich.

Einfluss auf Normenwerk:

Die Projektergebnisse sind nützlich im Hinblick auf künftige Revisionen der Normen und Empfehlungen.

Der Präsident/die Präsidentin der Begleitkommission:

Name: Anagnostou

Vorname: Georg

Amt, Firma, Institut: ETH Zürich

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:



## Verzeichnis der Berichte der Forschung im Strassenwesen

Bericht-Nr.	Projekt Nr.	Titel	Jahr
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1462	ASTRA 2011/004	Ermittlung der Versagensgrenze eines T2 Norm-Belages mit der mobiles Grossversuchsanlage MLS10	2014
1460	SVI 2007/017	Nutzen der Verkehrsinformation für die Verkehrssicherheit	2014
1459	VSS 2002/501	Leichtes Fallgewichtsgesetz für die Verdichtungskontrolle von Fundationsschichten	2014
1458	VSS 2010/703	Umsetzung Erhaltungsmanagement für Strassen in Gemeinden - Arbeitshilfen als Anhang zur Norm 640 980	2014
1457	SVI 2012/006	Forschungspaket VeSPA Teilprojekt 5: Medizinische Folgen des Strassenunfallgeschehens	2014
1456	SVI 2012/005	Forschungspaket VeSPA Teilprojekt 4: Einflüsse des Wetters auf das Strassenunfallgeschehen	2014
1455	SVI 2012/004	Forschungspaket VeSPA Teilprojekt 3: Einflüsse von Fahrzeugeigenschaften auf das Strassenunfallgeschehen	2014
1454	SVI 2012/003	Forschungspaket VeSPA Teilprojekt 2: Einflüsse von Situation und Infrastruktur auf das Strassenunfallgeschehen: Phase 1	2014
1453	SVI 2012/002	Forschungspaket VeSPA Teilprojekt 1: Einflüsse von Mensch und Gesellschaft auf das Strassenunfallgeschehen: Phase 1	2014
1452	SVI 2012/001	Forschungspaket VeSPA: Synthesebericht Phase 1	2014
1451	FGU 2010/006	Gasanalytik zur frühzeitigen Branddetektion in Tunneln	2013
1450	VSS 2002/401	Kaltrecycling von Ausbauasphalt mit bituminösen Bindemitteln	2014
1449	ASTRA 2010/024	E-Scooter - Sozial- und naturwissenschaftliche Beiträge zur Förderung leichter Elektrofahrzeuge in der Schweiz	2013
1448	SVI 2009/008	Anforderungen der Güterlogistik an die Netzinfrastruktur und die langfristige Netzentwicklung in der Schweiz. Forschungspaket UVEK/ASTRA "Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz", Teilprojekt C	2014
1447	SVI 2009/005	Informationstechnologien in der zukünftigen Gütertransportwirtschaft Forschungspaket UVEK/ASTRA "Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz", Teilprojekt E	2013
1446	VSS 2005/454	Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: EP3: Stofffluss- und Nachhaltigkeitsbeurteilung	2013

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1445	VSS 2009/301	Öffnung der Busstreifen für weitere Verkehrsteilnehmende	2013
1444	VSS 2007/306	Verkehrsqualität und Leistungsfähigkeit von Anlagen des leichten Zweirad- und des Fussgängerverkehrs	2013
1443	VSS 2007/305	Verkehrsqualität und Leistungsfähigkeit des strassengebundenen ÖV	2013
1442	SVI 2010/004	Messen des Nutzens von Massnahmen mit Auswirkungen auf den Langsamverkehr - Vorstudie	2013
1441_2	SVI 2009/010	Zielsystem im Güterverkehr. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz - Teilprojekt G	2013
1441_1	SVI 2009/010	Effizienzsteigerungspotenziale in der Transportwirtschaft durch integrierte Bewirtschaftungsinstrumente aus Sicht der Infrastrukturbetreiber Synthese der Teilprojekte B3, C, D, E und F des Forschungspakets Güterverkehr anhand eines Zielsystems für den Güterverkehr	2013
1440	SVI 2009/006	Benchmarking-Ansätze im Verkehrswesen	2013
1439	SVI 2009/002	Konzept zur effizienten Erfassung und Analyse der Güterverkehrsdaten Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz von Verkehrsmitteln im Güterverkehr der Schweiz TP A	2013
1438_2	SVI 2009/011	Ortsbezogene Massnahmen zur Reduktion der Auswirkungen des Güterverkehrs - Teil 2. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP H	2013
1438_1	SVI 2009/011	Ortsbezogene Massnahmen zur Reduktion der Auswirkungen des Güterverkehrs - Teil 1. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP H	2013
1437	VSS 2008/203	Trottoirüberfahrten und punktuelle Querungen ohne Vortritt für den Langsamverkehr	2013
1436	VSS 2010/401	Auswirkungen verschiedener Recyclinganteile in ungebundenen Gemischen	2013
1435	FGU 2008/007_OBF	Schadstoff- und Rauchkurzschlüsse bei Strassentunneln	2013
1434	VSS 2006/503	Performance Oriented Requirements for Bituminous Mixtures	2013
1433	ASTRA 2010/001	Güterverkehr mit Lieferwagen: Entwicklungen und Massnahmen Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP B3	2013
1432	ASTRA 2007/011	Praxis-Kalibrierung der neuen mobilen Grossversuchsanlage MLS10 für beschleunigte Verkehrslastsimulation auf Strassenbelägen in der Schweiz	2013
1431	ASTRA 2011/015	TeVeNOx - Testing of SCR-Systems on HD-Vehicles	2013
1430	ASTRA 2009/004	Impact des conditions météorologiques extrêmes sur la chaussée	2013
1429	SVI 2009/009	Einschätzungen der Infrastrukturnutzer zur Weiterentwicklung des Regulativs Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der	2013

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		Verkehrsmittel im Güterverkehr der Schweiz TP F	
1428	SVI 2010/005	Branchenspezifische Logistikkonzepte und Güterverkehrsaufkommen sowie deren Trends Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP B2	2013
1427	SVI 2006/002	Begegnungszonen - eine Werkschau mit Empfehlungen für die Realisierung	2013
1426	ASTRA 2010/025_OBF	Luftströmungsmessung in Strassentunneln	2013
1425	VSS 2005/401	Résistance à l'altération des granulats et des roches	2013
1424	ASTRA 2006/007	Optimierung der Baustellenplanung an Autobahnen	2013
1423	ASTRA 2010/012	Forschungspaket: Lärmarme Beläge innerorts EP3: Betrieb und Unterhalt lärmarmen Beläge	2013
1422	ASTRA 2011/006_OBF	Fracture processes and in-situ fracture observations in Gipskeuper	2013
1421	VSS 2009/901	Experimenteller Nachweis des vorgeschlagenen Raum- und Topologiemodells für die VM-Anwendungen in der Schweiz (MDATrafo)	2013
1420	SVI 2008/003	Projektiertungsfreiräume bei Strassen und Plätzen	2013
1419	VSS 2001/452	Stabilität der Polymere beim Heisseinbau von PmB-haltigen Strassenbelägen	2013
1418	VSS 2008/402	Anforderungen an hydraulische Eigenschaften von Geokunststoffen	2012
1417	FGU 2009/002	Heat Exchanger Anchors for Thermo-active Tunnels	2013
1416	FGU 2010/001	Sulfatwiderstand von Beton: verbessertes Verfahren basierend auf der Prüfung nach SIA 262/1, Anhang D	2013
1415	VSS 2010/A01	Wissenslücken im Infrastrukturmanagementprozess "Strasse" im Siedlungsgebiet	2013
1414	VSS 2010/201	Passive Sicherheit von Tragkonstruktionen der Strassenausstattung	2013
1413	SVI 2009/003	Güterverkehrsintensive Branchen und Güterverkehrsströme in der Schweiz Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz Teilprojekt B1	2013
1412	ASTRA 2010/020	Werkzeug zur aktuellen Gangliniennorm	2013
1411	VSS 2009/902	Verkehrstelematik für die Unterstützung des Verkehrsmanagements in ausserordentlichen Lagen	2013
1410	VSS 2010/202_OBF	Reduktion von Unfallfolgen bei Bränden in Strassentunneln durch Abschnittsbildung	2013
1409	ASTRA 2010/017_OBF	Regelung der Luftströmung in Strassentunneln im Brandfall	2013
1408	VSS 2000/434	Viellissement thermique des enrobés bitumineux en laboratoire	2012

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1407	ASTRA 2006/014	Fusion des indicateurs de sécurité routière : FUSAIN	2012
1406	ASTRA 2004/015	Amélioration du modèle de comportement individuel du Conducteur pour évaluer la sécurité d'un flux de trafic par simulation	2012
1405	ASTRA 2010/009	Potential von Photovoltaik an Schallschutzmassnahmen entlang der Nationalstrassen	2012
1404	VSS 2009/707	Validierung der Kosten-Nutzen-Bewertung von Fahrbahn-Erhaltungsmassnahmen	2012
1403	SVI 2007/018	Vernetzung von HLS- und HVS-Steuerungen	2012
1402	VSS 2008/403	Witterungsbeständigkeit und Durchdrückverhalten von Geokunststoffen	2012
1401	SVI 2006/003	Akzeptanz von Verkehrsmanagementmassnahmen-Vorstudie	2012
1400	VSS 2009/601	Begrünte Stützgitterböschungssysteme	2012
1399	VSS 2011/901	Erhöhung der Verkehrssicherheit durch Incentivierung	2012
1398	ASTRA 2010/019	Environmental Footprint of Heavy Vehicles Phase III: Comparison of Footprint and Heavy Vehicle Fee (LSVA) Criteria	2012
1397	FGU 2008/003_OBF	Brandschutz im Tunnel: Schutzziele und Brandbemessung Phase 1: Stand der Technik	2012
1396	VSS 1999/128	Einfluss des Umhüllungsgrades der Mineralstoffe auf die mechanischen Eigenschaften von Mischgut	2012
1395	FGU 2009/003	KarstALEA: Wegleitung zur Prognose von karstspezifischen Gefahren im Untertagbau	2012
1394	VSS 2010/102	Grundlagen Betriebskonzepte	2012
1393	VSS 2010/702	Aktualisierung SN 640 907, Kostengrundlage im Erhaltungsmanagement	2012
1392	ASTRA 2008/008_009	FEHRL Institutes WIM Initiative (Fiwi)	2012
1391	ASTRA 2011/003	Leitbild ITS-CH Landverkehr 2025/30	2012
1390	FGU 2008/004_OBF	Einfluss der Grundwasserströmung auf das Quellverhalten des Gipskeupers im Belchentunnel	2012
1389	FGU 2003/002	Long Term Behaviour of the Swiss National Road Tunnels	2012
1388	SVI 2007/022	Möglichkeiten und Grenzen von elektronischen Busspuren	2012
1387	VSS 2010/205_OBF	Ablage der Prozessdaten bei Tunnel-Prozessleitsystemen	2012
1386	VSS 2006/204	Schallreflexionen an Kunstbauten im Strassenbereich	2012
1385	VSS 2004/703	Bases pour la révision des normes sur la mesure et l'évaluation de la planéité des chaussées	2012
1384	VSS 1999/249	Konzeptuelle Schnittstellen zwischen der Basisdatenbank und EMF-, EMK- und EMT-DB	2012

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1383	FGU 2008/005	Einfluss der Grundwasserströmung auf das Quellverhalten des Gipskeupers im Chienbergtunnel	2012
1382	VSS 2001/504	Optimierung der statischen Eindringtiefe zur Beurteilung von harten Gussasphaltsorten	2012
1381	SVI 2004/055	Nutzen von Reisezeiteinsparungen im Personenverkehr	2012
1380	ASTRA 2007/009	Wirkungsweise und Potential von kombinierter Mobilität	2012
1379	VSS 2010/206_OBF	Harmonisierung der Abläufe und Benutzeroberflächen bei Tunnel-Prozessleitsystemen	2012
1378	SVI 2004/053	Mehr Sicherheit dank Kernfahrbahnen?	2012
1377	VSS 2009/302	Verkehrssicherheitsbeurteilung bestehender Verkehrsanlagen (Road Safety Inspection)	2012
1376	ASTRA 2011/008_004	Erfahrungen im Schweizer Betonbrückenbau	2012
1375	VSS 2008/304	Dynamische Signalisierungen auf Hauptverkehrsstrassen	2012
1374	FGU 2004/003	Entwicklung eines zerstörungsfreien Prüfverfahrens für Schweissnähte von KDB	2012
1373	VSS 2008/204	Vereinheitlichung der Tunnelbeleuchtung	2012
1372	SVI 2011/001	Verkehrssicherheitsgewinne aus Erkenntnissen aus Datapooling und strukturierten Datenanalysen	2012
1371	ASTRA 2008/017	Potenzial von Fahrgemeinschaften	2011
1370	VSS 2008/404	Dauerhaftigkeit von Betonfahrbahnen aus Betongranulat	2011
1369	VSS 2003/204	Rétention et traitement des eaux de chaussée	2012
1368	FGU 2008/002	Soll sich der Mensch dem Tunnel anpassen oder der Tunnel dem Menschen?	2011
1367	VSS 2005/801	Grundlagen betreffend Projektierung, Bau und Nachhaltigkeit von Anschlussgleisen	2011
1366	VSS 2005/702	Überprüfung des Bewertungshintergrundes zur Beurteilung der Strassengriffigkeit	2010
1365	SVI 2004/014	Neue Erkenntnisse zum Mobilitätsverhalten dank Data Mining?	2011
1364	SVI 2009/004	Regulierung des Güterverkehrs Auswirkungen auf die Transportwirtschaft Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP D	2012
1363	VSS 2007/905	Verkehrsprognosen mit Online -Daten	2011
1362	SVI 2004/012	Aktivitätenorientierte Analyse des Neuverkehrs	2012
1361	SVI 2004/043	Innovative Ansätze der Parkraumbewirtschaftung	2012
1360	VSS 2010/203	Akustische Führung im Strassentunnel	2012
1359	SVI 2004/003	Wissens- und Technologientransfer im Verkehrsbereich	2012

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1358	SVI 2004/079	Verkehrsanbindung von Freizeitanlagen	2012
1357	SVI 2007/007	Unaufmerksamkeit und Ablenkung: Was macht der Mensch am Steuer?	2012
1356	SVI 2007/014	Kooperation an Bahnhöfen und Haltestellen	2011
1355	FGU 2007/002	Prüfung des Sulfatwiderstandes von Beton nach SIA 262/1, Anhang D: Anwendbarkeit und Relevanz für die Praxis	2011
1354	VSS 2003/203	Anordnung, Gestaltung und Ausführung von Treppen, Rampen und Treppenwegen	2011
1353	VSS 2000/368	Grundlagen für den Fussverkehr	2011
1352	VSS 2008/302	Fussgängerstreifen (Grundlagen)	2011
1351	ASTRA 2009/001	Development of a best practice methodology for risk assessment in road tunnels	2011
1350	VSS 2007/904	IT-Security im Bereich Verkehrstelematik	2011
1349	VSS 2003/205	In-Situ-Abflussversuche zur Untersuchung der Entwässerung von Autobahnen	2011
1348	VSS 2008/801	Sicherheit bei Parallelführung und Zusammentreffen von Strassen mit der Schiene	2011
1347	VSS 2000/455	Leistungsfähigkeit von Parkieranlagen	2010
1346	ASTRA 2007/004	Quantifizierung von Leckagen in Abluftkanälen bei Strassentunneln mit konzentrierter Rauchabsaugung	2010
1345	SVI 2004/039	Einsatzbereiche verschiedener Verkehrsmittel in Agglomerationen	2011
1344	VSS 2009/709	Initialprojekt für das Forschungspaket "Nutzensteigerung für die Anwender des SIS"	2011
1343	VSS 2009/903	Basistechnologien für die intermodale Nutzungserfassung im Personenverkehr	2011
1342	FGU 2005/003	Untersuchungen zur Frostkörperbildung und Frosthebung beim Gefrierverfahren	2010
1341	FGU 2007/005	Design aids for the planning of TBM drives in squeezing ground	2011
1340	SVI 2004/051	Aggressionen im Verkehr	2011
1339	SVI 2005/001	Widerstandsfunktionen für Innerorts-Strassenabschnitte ausserhalb des Einflussbereiches von Knoten	2010
1338	VSS 2006/902	Wirkungsmodelle für fahrzeugseitige Einrichtungen zur Steigerung der Verkehrssicherheit	2009
1337	ASTRA 2006/015	Development of urban network travel time estimation methodology	2011
1336	ASTRA 2007/006	SPIN-ALP: Scanning the Potential of Intermodal Transport on Alpine Corridors	2010
1335	VSS 2007/502	Stripping bei lärmindernden Deckschichten unter Überrollbeanspruchung im Labormassstab	2011

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1334	ASTRA 2009/009	Was treibt uns an? Antriebe und Treibstoffe für die Mobilität von Morgen	2011
1333	SVI 2007/001	Standards für die Mobilitätsversorgung im peripheren Raum	2011
1332	VSS 2006/905	Standardisierte Verkehrsdaten für das verkehrsträgerübergreifende Verkehrsmanagement	2011
1331	VSS 2005/501	Rückrechnung im Strassenbau	2011
1330	FGU 2008/006	Energiegewinnung aus städtischen Tunneln: Systemevaluation	2010
1329	SVI 2004/073	Alternativen zu Fussgängerstreifen in Tempo-30-Zonen	2010
1328	VSS 2005/302	Grundlagen zur Quantifizierung der Auswirkungen von Sicherheitsdefiziten	2011
1327	VSS 2006/601	Vorhersage von Frost und Nebel für Strassen	2010
1326	VSS 2006/207	Erfolgskontrolle Fahrzeugrückhaltesysteme	2011
1325	SVI 2000/557	Indices caractéristiques d'une cité-vélo. Méthode d'évaluation des politiques cyclables en 8 indices pour les petites et moyennes communes.	2010
1324	VSS 2004/702	Eigenheiten und Konsequenzen für die Erhaltung der Strassenverkehrsanlagen im überbauten Gebiet	2009
1323	VSS 2008/205	Ereignisdetektion im Strassentunnel	2011
1322	SVI 2005/007	Zeitwerte im Personenverkehr: Wahrnehmungs- und Distanzabhängigkeit	2008
1321	VSS 2008/501	Validation de l'oedomètre CRS sur des échantillons intacts	2010
1320	VSS 2007/303	Funktionale Anforderungen an Verkehrserfassungssysteme im Zusammenhang mit Lichtsignalanlagen	2010
1319	VSS 2000/467	Auswirkungen von Verkehrsberuhigungsmassnahmen auf die Lärmimmissionen	2010
1318	FGU 2006/001	Langzeitquellversuche an anhydritführenden Gesteinen	2010
1317	VSS 2000/469	Geometrisches Normalprofil für alle Fahrzeugtypen	2010
1316	VSS 2001/701	Objektorientierte Modellierung von Strasseninformationen	2010
1315	VSS 2006/904	Abstimmung zwischen individueller Verkehrsinformation und Verkehrsmanagement	2010
1314	VSS 2005/203	Datenbank für Verkehrsaufkommensraten	2008
1313	VSS 2001/201	Kosten-/Nutzenbetrachtung von Strassenentwässerungssystemen, Ökobilanzierung	2010
1312	SVI 2004/006	Der Verkehr aus Sicht der Kinder: Schulwege von Primarschulkindern in der Schweiz	2010
1311	VSS 2000/543	VIABILITE DES PROJETS ET DES INSTALLATIONS ANNEXES	2010

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1310	ASTRA 2007/002	Beeinflussung der Luftströmung in Strassentunneln im Brandfall	2010
1309	VSS 2008/303	Verkehrsregelungssysteme - Modernisierung von Lichtsignalanlagen	2010
1308	VSS 2008/201	Hindernisfreier Verkehrsraum - Anforderungen aus Sicht von Menschen mit Behinderung	2010
1307	ASTRA 2006/002	Entwicklung optimaler Mischgüter und Auswahl geeigneter Bindemittel; D-A-CH - Initialprojekt	2008
1306	ASTRA 2008/002	Strassenglätte-Prognosesystem (SGPS)	2010
1305	VSS 2000/457	Verkehrserzeugung durch Parkieranlagen	2009
1304	VSS 2004/716	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen	2008
1303	ASTRA 2009/010	Geschwindigkeiten in Steigungen und Gefällen; Überprüfung	2010
1302	VSS 1999/131	Zusammenhang zwischen Bindemittleigenschaften und Schadensbildern des Belages?	2010
1301	SVI 2007/006	Optimierung der Strassenverkehrsunfallstatistik durch Berücksichtigung von Daten aus dem Gesundheitswesen	2009
1300	VSS 2003/903	SATELROU Perspectives et applications des méthodes de navigation pour la télématique des transports routiers et pour le système d'information de la route	2010
1299	VSS 2008/502	Projet initial - Enrobés bitumineux à faibles impacts énergétiques et écologiques	2009
1298	ASTRA 2007/012	Griffigkeit auf winterlichen Fahrbahnen	2010
1297	VSS 2007/702	Einsatz von Asphaltbewehrungen (Asphalteinlagen) im Erhaltungsmanagement	2009
1296	ASTRA 2007/008	Swiss contribution to the Heavy-Duty Particle Measurement Programme (HD-PMP)	2010
1295	VSS 2005/305	Entwurfgrundlagen für Lichtsignalanlagen und Leitfaden	2010
1294	VSS 2007/405	Wiederhol- und Vergleichspräzision der Druckfestigkeit von Gesteinskörnungen am Haufwerk	2010
1293	VSS 2005/402	Détermination de la présence et de l'efficacité de dope dans les bétons bitumineux	2010
1292	ASTRA 2006/004	Entwicklung eines Pflanzenöl-Blockheizkraftwerkes mit eigener Ölmühle	2010
1291	ASTRA 2009/005	Fahrmuster auf überlasteten Autobahnen Simultanes Berechnungsmodell für das Fahrverhalten auf Autobahnen als Grundlage für die Berechnung von Schadstoffemissionen und Fahrzeitgewinnen	2010
1290	VSS 1999/209	Conception et aménagement de passages inférieurs et supérieurs pour piétons et deux-roues légers	2008

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1289	VSS 2005/505	Affinität von Gesteinskörnungen und Bitumen, nationale Umsetzung der EN	2010
1288	ASTRA 2006/020	Footprint II - Long Term Pavement Performance and Environmental Monitoring on A1	2010
1287	VSS 2008/301	Verkehrsqualität und Leistungsfähigkeit von komplexen ungesteuerten Knoten: Analytisches Schätzverfahren	2009
1286	VSS 2000/338	Verkehrsqualität und Leistungsfähigkeit auf Strassen ohne Richtungstrennung	2010
1285	VSS 2002/202	In-situ Messung der akustischen Leistungsfähigkeit von Schallschirmen	2009
1284	VSS 2004/203	Evacuation des eaux de chaussée par les bas-cotés	2010
1283	VSS 2000/339	Grundlagen für eine differenzierte Bemessung von Verkehrsanlagen	2008
1282	VSS 2004/715	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen: Zusatzkosten infolge Vor- und Aufschub von Erhaltungsmaßnahmen	2010
1281	SVI 2004/002	Systematische Wirkungsanalysen von kleinen und mittleren Verkehrsvorhaben	2009
1280	ASTRA 2004/016	Auswirkungen von fahrzeuginternen Informationssystemen auf das Fahrverhalten und die Verkehrssicherheit Verkehrspsychologischer Teilbericht	2010
1279	VSS 2005/301	Leistungsfähigkeit zweistreifiger Kreisel	2009
1278	ASTRA 2004/016	Auswirkungen von fahrzeuginternen Informationssystemen auf das Fahrverhalten und die Verkehrssicherheit - Verkehrstechnischer Teilbericht	2009
1277	SVI 2007/005	Multimodale Verkehrsqualitätsstufen für den Strassenverkehr - Vorstudie	2010
1276	VSS 2006/201	Überprüfung der schweizerischen Ganglinien	2008
1275	ASTRA 2006/016	Dynamic Urban Origin - Destination Matrix - Estimation Methodology	2009
1274	SVI 2004/088	Einsatz von Simulationswerkzeugen in der Güterverkehrs- und Transportplanung	2009
1273	ASTRA 2008/006	UNTERHALT 2000 - Massnahme M17, FORSCHUNG: Dauerhafte Materialien und Verfahren SYNTHESE - BERICHT zum Gesamtprojekt "Dauerhafte Beläge" mit den Einzelnen Forschungsprojekten: - ASTRA 200/419: Verhaltensbilanz der Beläge auf Nationalstrassen - ASTRA 2000/420: Dauerhafte Komponenten auf der Basis erfolgreicher Strecken - ASTRA 2000/421: Durabilité des enrobés - ASTRA 2000/422: Dauerhafte Beläge, Rundlaufversuch - ASTRA 2000/423: Griffigkeit der Beläge auf Autobahnen, Vergleich zwischen den Messergebnissen von SRM und SCRIM - ASTRA 2008/005: Vergleichsstrecken mit unterschiedlichen oberen Tragschichten auf einer Nationalstrasse	2008
1272	VSS 2007/304	Verkehrsregelungssysteme - behinderte und ältere Menschen an Lichtsignalanlagen	2010
1271	VSS 2004/201	Unterhalt von Lärmschirmen	2009

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1270	VSS 2005/502	Interaktion Strasse Hangstabilität: Monitoring und Rückwärtsrechnung	2009
1269	VSS 2005/201	Evaluation von Fahrzeugrückhaltesystemen im Mittelstreifen von Autobahnen	2009
1268	ASTRA 2005/007	PM10-Emissionsfaktoren von Abriebspartikeln des Strassenverkehrs (APART)	2009
1267	VSS 2007/902	MDA in SVT Einsatz modellbasierter Datentransfernormen (INTERLIS) in der Strassenverkehrstelematik	2009
1266	VSS 2000/343	Unfall- und Unfallkostenraten im Strassenverkehr	2009
1265	VSS 2005/701	Zusammenhang zwischen dielektrischen Eigenschaften und Zustandsmerkmalen von bitumenhaltigen Fahrbahnbelägen (Pilotuntersuchung)	2009
1264	SVI 2004/004	Verkehrspolitische Entscheidungsfindung in der Verkehrsplanung	2009
1263	VSS 2001/503	Phénomène du dégel des sols gélifs dans les infrastructures des voies de communication et les pergélisols alpins	2006
1262	VSS 2003/503	Lärmverhalten von Deckschichten im Vergleich zu Gussasphalt mit strukturierter Oberfläche	2009
1261	ASTRA 2004/018	Pilotstudie zur Evaluation einer mobilen Grossversuchsanlage für beschleunigte Verkehrslastsimulation auf Strassenbelägen	2009
1260	FGU 2005/001	Testeinsatz der Methodik "Indirekte Vorauserkundung von wasserführenden Zonen mittels Temperaturdaten anhand der Messdaten des Lötschberg-Basistunnels	2009
1259	VSS 2004/710	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen - Synthesebericht	2008
1258	VSS 2005/802	Kaphaltestellen Anforderungen und Auswirkungen	2009
1257	SVI 2004/057	Wie Strassenraumbilder den Verkehr beeinflussen Der Durchfahrtswiderstand als Arbeitsinstrument bei der städtebaulichen Gestaltung von Strassenräumen	2009
1256	VSS 2006/903	Qualitätsanforderungen an die digitale Videobild-Bearbeitung zur Verkehrsüberwachung	2009
1255	VSS 2006/901	Neue Methoden zur Erkennung und Durchsetzung der zulässigen Höchstgeschwindigkeit	2009
1254	VSS 2006/502	Drains verticaux préfabriqués thermiques pour la consolidation in-situ des sols	2009
1253	VSS 2001/203	Rétention des polluants des eaux de chaussées selon le système "infiltrations sur les talus". Vérification in situ et optimisation	2009
1252	SVI 2003/001	Nettoverkehr von verkehrintensiven Einrichtungen (VE)	2009
1251	ASTRA 2002/405	Incidence des granulats arrondis ou partiellement arrondis sur les propriétés d'adhérence des bétons bitumineux	2008
1250	VSS 2005/202	Strassenabwasser Filterschacht	2007

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1249	FGU 2003/004	Einflussfaktoren auf den Brandwiderstand von Betonkonstruktionen	2009
1248	VSS 2000/433	Dynamische Eindringtiefe zur Beurteilung von Gussasphalt	2008
1247	VSS 2000/348	Anforderungen an die strassenseitige Ausrüstung bei der Umwidmung von Standstreifen	2009
1246	VSS 2004/713	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen: Bedeutung Oberflächenzustand und Tragfähigkeit sowie gegenseitige Beziehung für Gebrauchs- und Substanzwert	2009
1245	VSS 2004/701	Verfahren zur Bestimmung des Erhaltungsbedarfs in kommunalen Strassennetzen	2009
1244	VSS 2004/714	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen - Gesamtnutzen und Nutzen-Kosten-Verhältnis von standardisierten Erhaltungsmassnahmen	2008
1243	VSS 2000/463	Kosten des betrieblichen Unterhalts von Strassenanlagen	2008
1242	VSS 2005/451	Recycling von Ausbaupasphalt in Heissmischgut	2007
1241	ASTRA 2001/052	Erhöhung der Aussagekraft des LCPC Spurbildungstests	2009
1240	ASTRA 2002/010	L'acceptabilité du péage de congestion : Résultats et analyse de l'enquête en Suisse	2009
1239	VSS 2000/450	Bemessungsgrundlagen für das Bewehren mit Geokunststoffen	2009
1238	VSS 2005/303	Verkehrssicherheit an Tagesbaustellen und bei Anschlüssen im Baustellenbereich von Hochleistungsstrassen	2008
1237	VSS 2007/903	Grundlagen für eCall in der Schweiz	2009
1236	ASTRA 2008/008_07	Analytische Gegenüberstellung der Strategie- und Tätigkeitsschwerpunkte ASTRA-AIPCR	2008
1235	VSS 2004/711	Forschungspaket Massnahmenplanung im EM von Fahrbahnen - Standardisierte Erhaltungsmassnahmen	2008
1234	VSS 2006/504	Expérimentation in situ du nouveau drainomètre européen	2008
1233	ASTRA 2000/420	Unterhalt 2000 Forschungsprojekt FP2 Dauerhafte Komponenten bitumenhaltiger Belagsschichten	2009
660	AGB 2008/002	Indirekt gelagerte Betonbrücken - Sachstandsbericht	2014
659	AGB 2009/014	Suizidprävention bei Brücken: Follow-Up	2014
658	AGB 2006/015_OBF	Querkraftwiderstand vorgespannter Brücken mit ungenügender Querkraftbewehrung	2014
657	AGB 2003/012	Brücken in Holz: Möglichkeiten und Grenzen	2013
656	AGB 2009/015	Experimental verification of integral bridge abutments	2013

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655	AGB 2007/004	Fatigue Life Assessment of Roadway Bridges Based on Actual Traffic Loads	2013
654	AGB 2005-008	Thermophysical and Thermomechanical Behavior of Cold-Curing Structural Adhesives in Bridge Construction	2013
653	AGB 2007/002	Poinçonnement des pontsdalles précontraints	2013
652	AGB 2009/006	Detektion von Betonstahlbrüchen mit der magnetischen Streufeldmethode	2013
651	AGB 2006/006_OBF	Instandsetzung und Monitoring von AAR-geschädigten Stützmauern und Brücken	2013
650	AGB 2005/010	Korrosionsbeständigkeit von nichtrostenden Betonstählen	2012
649	AGB 2008/012	Anforderungen an den Karbonatisierungswiderstand von Betonen	2012
648	AGB 2005/023 + AGB 2006/003	Validierung der AAR-Prüfungen für Neubau und Instandsetzung	2011
647	AGB 2004/010	Quality Control and Monitoring of electrically isolated post-tensioning tendons in bridges	2011
646	AGB 2005/018	Interactin sol-structure : ponts à culées intégrales	2010
645	AGB 2005/021	Grundlagen für die Verwendung von Recyclingbeton aus Betongranulat	2010
644	AGB 2005/004	Hochleistungsfähiger Faserfeinkornbeton zur Effizienzsteigerung bei der Erhaltung von Kunstbauten aus Stahlbeton	2010
643	AGB 2005/014	Akustische Überwachung einer stark geschädigten Spannbetonbrücke und Zustandserfassung beim Abbruch	2010
642	AGB 2002/006	Verbund von Spanngliedern	2009
641	AGB 2007/007	Empfehlungen zur Qualitätskontrolle von Beton mit Luftpermeabilitätsmessungen	2009
640	AGB 2003/011	Nouvelle méthode de vérification des ponts mixtes à âme pleine	2010
639	AGB 2008/003	RiskNow-Falling Rocks Excel-basiertes Werkzeug zur Risikoermittlung bei Steinschlagschutzgalerien	2010
638	AGB2003/003	Ursachen der Rissbildung in Stahlbetonbauwerken aus Hochleistungsbeton und neue Wege zu deren Vermeidung	2008
637	AGB 2005/009	Détermination de la présence de chlorures à l'aide du Géoradar	2009
636	AGB 2002/028	Dimensionnement et vérification des dalles de roulement de ponts routiers	2009
635	AGB 2004/002	Applicabilité de l'enrobé drainant sur les ouvrages d'art du réseau des routes nationales	2008
634	AGB 2002/007	Untersuchungen zur Potenzialfeldmessung an Stahlbetonbauten	2008
633	AGB 2002/014	Oberflächenschutzsysteme für Betontragwerke	2008

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632	AGB 2008/201	Sicherheit des Verkehrssystem Strasse und dessen Kunstbauten Testregion - Methoden zur Risikobeurteilung Schlussbericht	2010
631	AGB 2000/555	Applications structurales du Béton Fibré à Ultra-hautes Performances aux ponts	2008
630	AGB 2002/016	Korrosionsinhibitoren für die Instandsetzung chloridverseuchter Stahlbetonbauten	2010
629	AGB 2003/001 + AGB 2005/019	Integrale Brücken - Sachstandsbericht	2008
628	AGB 2005/026	Massnahmen gegen chlorid-induzierte Korrosion und zur Erhöhung der Dauerhaftigkeit	2008
627	AGB 2002/002	Eigenschaften von normalbreiten und überbreiten Fahrbahnübergängen aus Polymerbitumen nach starker Verkehrsbelastung	2008
626	AGB 2005/110	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Baustellensicherheit bei Kunstbauten	2009
625	AGB 2005/109	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen bei Kunstbauten	2009
624	AGB 2005/108	Sicherheit des Verkehrssystems / Strasse und dessen Kunstbauten / Risikobeurteilung für Kunstbauten	2010
623	AGB 2005/107	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Tragsicherheit der bestehenden Kunstbauten	2009
622	AGB 2005/106	Rechtliche Aspekte eines risiko- und effizienzbasierten Sicherheitskonzepts	2009
621	AGB 2005/105	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten Szenarien der Gefahrenentwicklung	2009
620	AGB 2005/104	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen	2009
619	AGB 2005/103	Sicherheit des Verkehrssystems / Strasse und dessen Kunstbauten / Ermittlung des Netzrisikos	2010
618	AGB 2005/102	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Methodik zur vergleichenden Risikobeurteilung	2009
617	AGB 2005/100	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten Synthesebericht	2010
616	AGB 2002/020	Beurteilung von Risiken und Kriterien zur Festlegung akzeptierter Risiken in Folge aussergewöhnlicher Einwirkungen bei Kunstbauten	2009