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Assessing the Correlation Between Headlight Safety Performance Rating (HSPR) and the Visibility Level for varying Object Reflection Coefficients

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Abstract

This paper explores the correlation between the Headlight Safety Performance Rating (HSPR) and the Visibility Level (VL). HSPR, a well-established metric, assesses headlight distributions by integrating key lighting functions to provide a comprehensive evaluation of a headlight system's overall performance. This evaluation encompasses aspects such as beam width, illumination distance and adaptation to road curvature. Meanwhile, VL, a contrast threshold-based metric, incorporates factors like driver age, object dimensions, and background luminance, offering a quantitative measure of object detection capabilities. Employing a simulation-based approach, this study models headlight intensity distributions based on street surface reflection characteristics, using a grid of object positions in simplified scenarios. The analysis primarily focuses on the specific properties of light distributions, such as intensity and, notably, beam patterns, to determine their impact on the correlation between both metrics. This study incorporates a variation of reflection coefficients of grey card objects and their influence on the correlation.

Keywords: HSPR, Headlight Rating, Object Detection, Visibility Level

Introduction

This paper explores the relationship between the headlight safety performance rating (HSPR) and the Visibility Level (VL) metric, specifically focusing on how object detection changes with calculated HSPR scores. The VL-metric is defined as the difference of object luminance to surrounding luminance divided by the perceivable luminance difference threshold [1]. With this aim, this paper will relate the headlight lighting distribution on the road and the potential of object detection. A special focus of this paper is on the correlation of various object reflection coefficients to get a feel for how well HSPR can represent this.

In CIE 188:2010, the HSPR is defined [2]. It is based on sixteen headlight systems and their corresponding light distributions. Light and its perception are highly subjective. Therefore, the aim of the HSPR is to obtain an objective measure of how good headlights are and make them comparable. To achieve this, various factors, points, and zones are being evaluated and weighted against each other for different lighting functions. That includes low beam (LB), high beam, and adaptive driving beam. The focus of this paper is on low beam as it has specific zones that are related to the streets surface and therefore allow for a direct comparison with objects that are placed on top of it.

In determining the overall score that a headlight system achieves in HSPR, there are certain factors, such as overall luminous flux and glare, which do not directly correlate with the driver's object visibility capabilities in the simple scenarios used for this study. Hence, these factors are excluded from this investigation, as the focus is on object detection represented by the VL.

The relevant zones for LB are displayed in Figure 1. Zone A, Zone B and D are mainly responsible for lane guidance and object detection. Zone B is angled at 5° to provide guidance for curves.

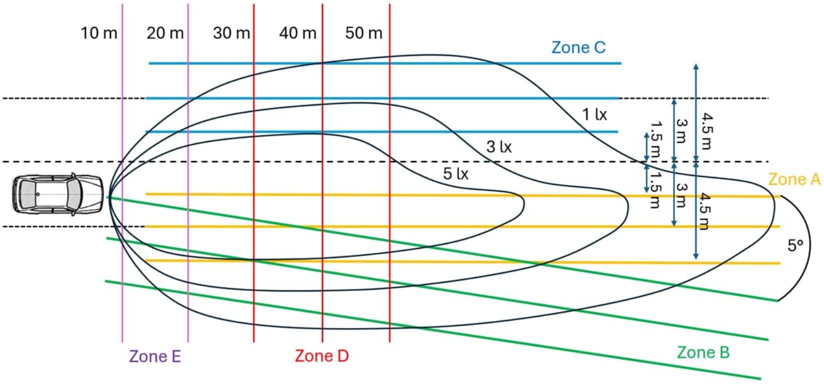

Figure 1 Schematics of the HSPR low beam zones which are evaluated for the corresponding scores.

Zone C is responsible for pedestrian detection, so its illuminances levels are calculated at the height of 250 mm above street level, meant for leg detection, corresponding to the middle of shin height.

Zone E is designed for intersections and pedestrian detection, also assessed at 250 mm height.

It is important to clarify that when illuminances are mentioned in the context of HSPR, it refers to vertical illuminances, meaning the illuminance on a vertically standing object perpendicular to the road.

For the zones A - C the Isolux lines at 1 lx, 3 lx and 5 lx are determined, and their intersection points with the lines shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** are calculated. Based on these nine distances for each zone, the respective means are being calculated and used for the overall score calculation.

For zones D and E, the procedure is similar except that only 3 lx is used, and the width intersection is calculated instead of the longitudinal distance.

The visibility level calculations are based on the model proposed by Adrian [1]. The calculated value is also called VL as short for visibility level. The model is based on the difference between the object luminance and its surrounding luminance, with the proportion of the difference relative to a detectable luminance difference threshold being a key factor. The majority of research regarding visibility level is based on the use of small quadratic objects, referred to as "grey cards" with a side length of 18 to 20 centimetres. This size is derived from the definition of critical objects. Larger objects lead to significant damages and safety issues when overrun.

In the existing literature, a wide range of visibility levels are determined for varying situations. Adrian's research indicates that a VL of 6 to 7 is a minimum requirement for safe driving [3].

Buyukkinaci also determines a VL of 7 to 8.5 in a laboratory setting, like the original studies on which the model is based [4]. It is established that laboratory settings yield contrasts and visibility levels that are lower than those required for detection tasks in real-world scenarios.

Bremond's study resulted in a VL of 7 as well for a rather simple visual task [5].

Chen's findings indicated that a VL of 7 may be adequate for the majority of tasks in relatively straightforward scenarios. However, for enhanced detection capabilities and dynamic driving tasks, a value of 21 may be more appropriate [6].

Ising's study resulted in a median of VL = 18 for alert, and up to 89 for unalert drivers [7]. This shows the wide range of necessary VL depending on the situation.

Paulmier's studies investigated the impact of background complexity and lead to a VL of 10 for simple scenarios and up to 25 or even 35 are necessary for 100% detection probabilities in complex backgrounds [8].

Erkan et al. conducted two studies. The first one was conducted in a lighting tunnel as a controlled environment with a real car and headlights. The second study used the same car but was conducted on an airfield leading to a more realistic rural environment. The former resulted in a VL suggestion of 13.35 and the later in VL = 25 [9].

All those studies vary in terms of their calculation inputs, as well as scenarios and visual task they employ.

The results can be roughly classified into three categories. One for a bare minimum of object visibility at a VL of 7, a relatively secure detection is taken as a middle ground between 13.35 and 18 at about 15 and a save detection in a more complex or dynamic scenario with 35. These categories will subsequently be used to define Iso-VL lines comparable to commonly used Iso-Lux lines but specifically for object detection.

Methodology

The HSPR score is calculated by the official software, which can be found at https://github.com/HSPR-Software/HSPR.

All headlight systems are simulated by light intensity distributions (LID) of real cars with the left and right headlights positioned 1.5 m apart. So, 0.75 m each from the middle axis of the car which is placed on the middle of the own driving lane. The height is set to 0.70 m. These are the requisite parameters for calculating HSPR.

The luminances required for the VL calculations are determined by a self-written Python program. It is purely based on direct illumination calculated from the photometric distance law. The light intensity is taken directly from the LID. This means that no reflections from the street increase the object luminance and vice versa.

The objects are represented by quadratic planes with a side length of 20 cm, which is consistent with the dimensions of the grey cards used in the majority of the cited studies. The objects are positioned with their normal vector in direction of the driver, so that the observed object surface size does not change due to the angle.

Grey cards are simulated with reflection coefficients of 4%, 8% and 12% to represent a variety of darker and realistic materials. They are assumed to have completely diffuse (Lambertian) reflection characteristics. The street surface is represented by a luminance coefficient for backwards reflection of the own car headlights to the driver of 14.8 mcd/($m^2 \cdot$lx) according to measurements from Köhler [10]. It is used for the whole streets surfaces luminance calculations.

For the VL calculation the following values are being used:

Age = 48 years as the mean age based on the amount of driving certificates in Germany [11] with the chip card format. This excludes certain antiquated driver's licences and focuses on individuals who have updated their licences to conform to the specified format.

Therefore, as a mean it does not represent the worst case scenario with older and potentially visually impaired drivers. Rather, it is representative of the mean of the actively driving population.

The surrounding luminance is determined by simulating the datapoints near the object specifically on the left and right side as well as above the object. Ignoring the lower side that would correspond to the street luminance right in front of the object. This leads to a lower overall surrounding luminance compared to picking the street surface as a reference. Picking the side next to the object with the maximum contrast, which would be the upper side, would lead to surrounding luminance unrealistically close to 0 cd/m^2, depending on the sky's illumination. To accommodate this, the simulation sets values with 0 cd/m^2 to 0.02 cd/m^2 to reach a slight offset to more realistic luminance in rural scenarios and to allow a better comparison to a luminance camera base evaluation. The left and right side are incorporated to be more in line with procedures used in the initially stated research and mitigating some of the evaluation deviations stated by Buyukkinaci when using the mean value all around the object [12].

The observation time is set to t = 350 ms assuming that the majority of authors picked 350 ms or the originally from Adrian stated 200 ms.

Given the higher luminance coefficient of the grey cards in combination with the metric of background luminance determination, this consistently yields a positive contrast when the street and objects illuminated purely by headlights. The headlight position is identical to that described for HSPR above.

A total of 17 different headlight systems is used for this paper. A simulation example for visualisation purposes is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

In contrast to the figure displayed, the simulation that was actually executed employs a matrix with one object position every 0.33 m on the width axis and one position every 0.5 m on the length axis. This results in a resolution that is significantly higher than that displayed here, leading to a reduction in errors made during the intersection determination and to improved interpolation.

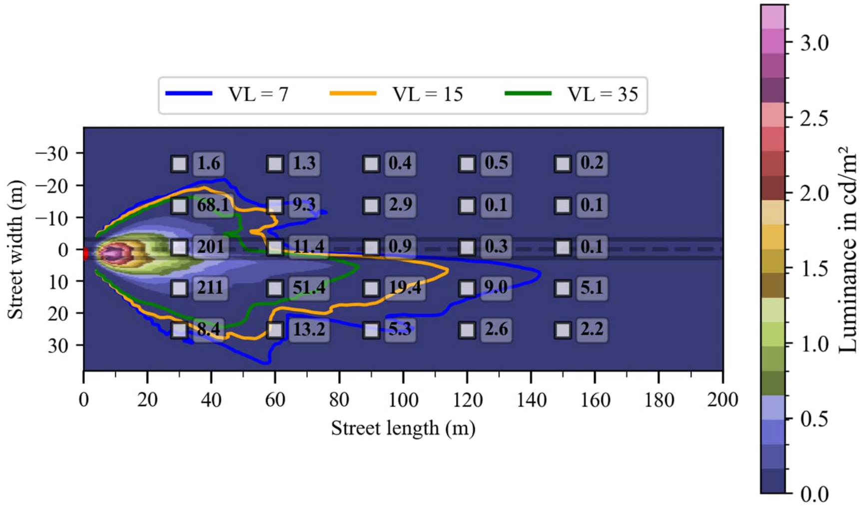

Figure 2 Example simulation of a specific headlight system. Grey cards are shown as squares with their corresponding VL and the resulting Iso-VL contours. Both left and right headlight positions are marked by red dots.

Results and Discussion

The methodology described herein results in the same number of intersections with Iso-VL lines as HSPR uses for the internal calculation, in order to analyse the relation between them.

As demonstrated in Figure 3, a highly significant correlation is evident between HSPR and the object detection distance for the VL target of 7. It has been established that the majority of R^2 values are close to 0.90, with a number of values even reaching 0.959.

At a higher target value of VL = 15, the correlation decreases slightly in most cases at lower reflection coefficients, while a significant increase is observed at 12%. At even higher VL, R^2 drops drastically, with significant differences from the linear representation of the data points, at least in Zone A at 4%. For higher ρ, the very good approximation can be maintained.

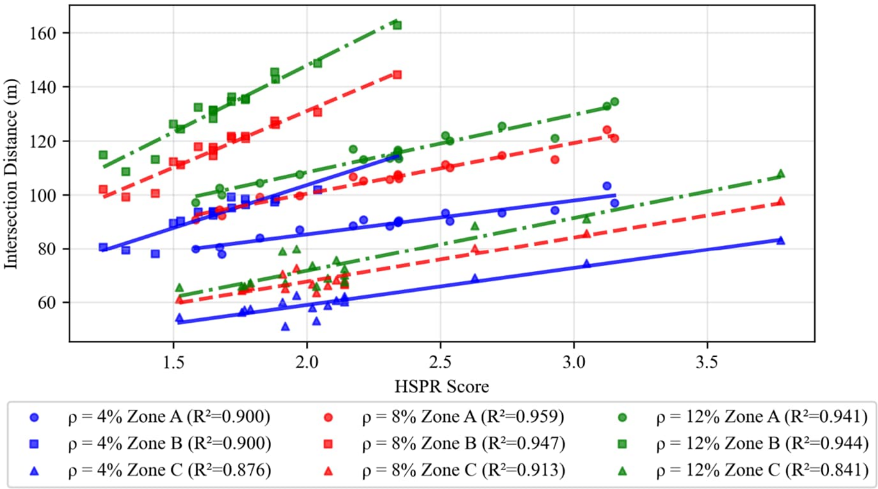

Figure 3 Mean of the three Iso-VL intersection distances over HSPR scores for Zones A, B and C with a VL target of 7 and varying reflection coefficients.

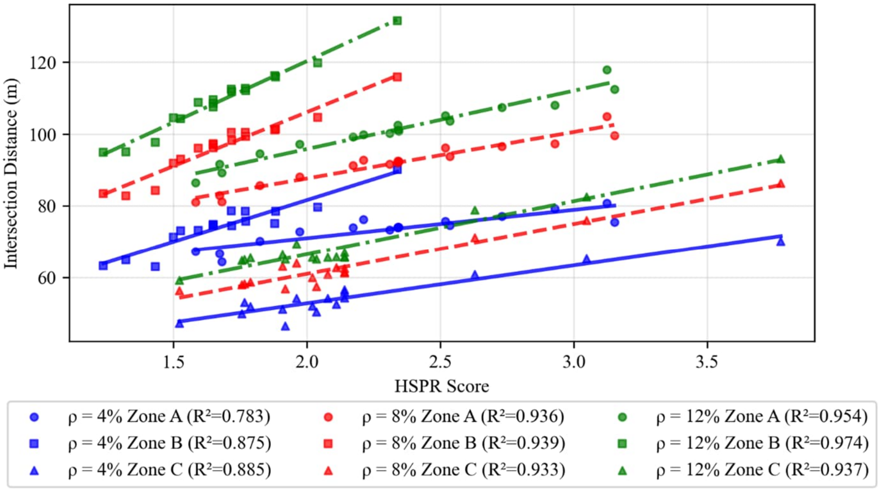

Figure 4 Mean of the three Iso-VL intersection distances over HSPR scores for Zones A, B and C with a VL target of 15 and varying reflection coefficients.

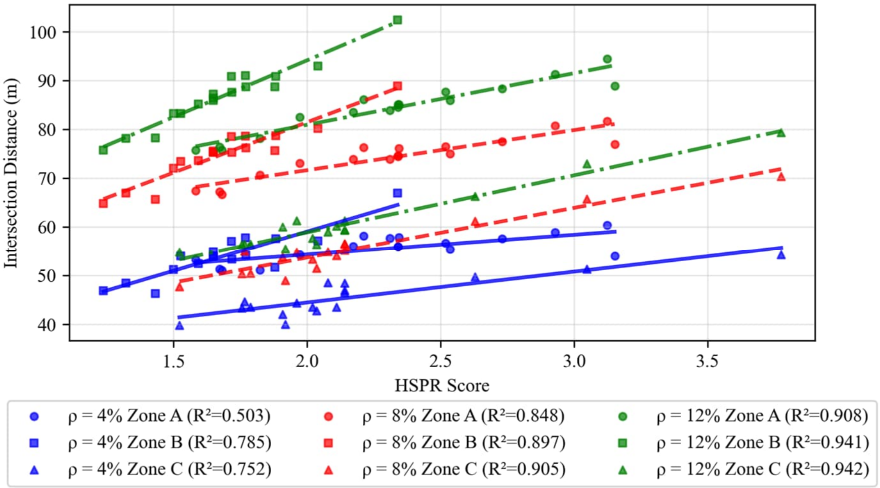

Figure 5 Mean of the three Iso-VL intersection distances over HSPR scores for Zones A, B and C with a VL target of 35 and varying reflection coefficients.

It is evident that Zone A is significantly impacted by the beam pattern, which rendering it susceptible to variations from LID to LID. In the case of certain headlights, the cut-off region may blend into the adjacent driving lane. The sharp edge can raise the overall mean value of this zone by values on the 1.5 m line. It is conceivable that the 1.5 m line only achieves half the distance of the 4.5 m line. In contrast, the discrepancy can be less pronounced for other LIDs. The values of Zone A are distributed over a wide range, with scores ranging from 1.6 to 3.2. This provides a good representation of the progression of detection distance by increased HSPR scores.

Zone B is highly robust across all variations in reflection coefficient and VL. Even at VL35 and 4%, where Zone A struggles, it maintains a comparatively high correlation. This may be due to the nature of the zone. It is not limited by rapid changes in cut-off zones and other requirements, which lead to fewer deviations in the evaluation, since the isolines are continuous and monotonous.

Specifically for Zone C, it should be noted that the significance of such a correlation is limited due to the clusters of data points very close to each other within the HSPR range of 1.75 to 2.20. This is due to the required cut-off region imposed by ECE regulations, which naturally limits the detection distance to approximately 40–65 m. For this reason, the correlation development is the least affected by changes in VL or reflection coefficients.

For the most part, there is a good correlation in Zone D, which is notably higher for higher reflection coefficients. This is because they lead to higher detection distances, avoiding the effect of obstruction by the cut-off region. This results in some cases where the offside distance is 0 m, which reduces the mean of the three combined values (at 30 m, 40 m and 50 m) for that zone, leading to a high deviation from the linear regression. This is why, in most cases, the onside has a higher R² than the offside. Without the last line at 50 m, the correlation is assumed to be notably higher, since the lines at 30 m and 40 m are generally steady and close to each other.

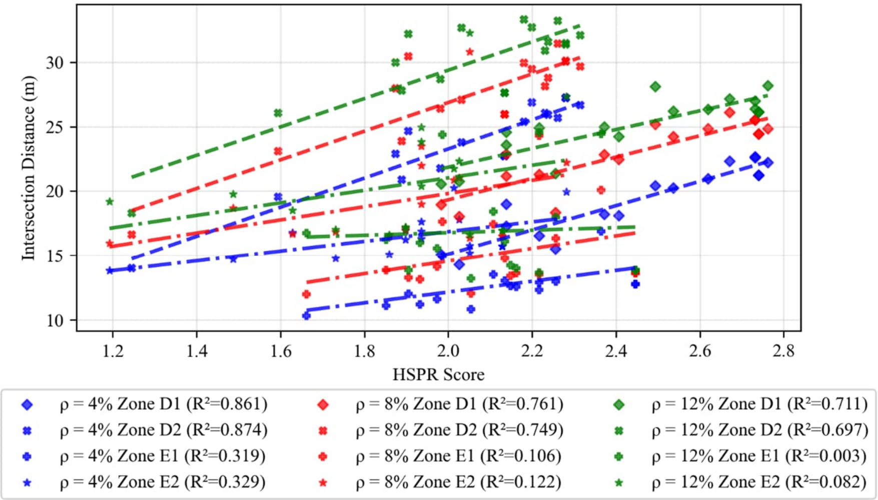

Figure 6 Mean of the three Iso-VL intersection distances over HSPR scores for Zones D and E, with each a nearside (numbered 1) and offside (numbered 2) with a VL target of 7 and varying reflection coefficients.

From Figures 6 to 8, the deviation from the linear estimate in Zone D only declines for the reflection coefficients of 4%, but increases for higher coefficients for the aforementioned reason that, for lower coefficients, the deviations at the 50 m line are enhanced due to the visibility limits being closer to that range.

In Zone E, an increased R² is observed for all reflection coefficients with increasing VL targets. In this zone, depending on the setting, the angles imposed by objects at distances of 6 to 25 m are very high, even at the 10 or 20 m line. These cases have considerable differences in the LID due to beam patterns for width illumination. This leads to additional deviation caused by discontinuities.

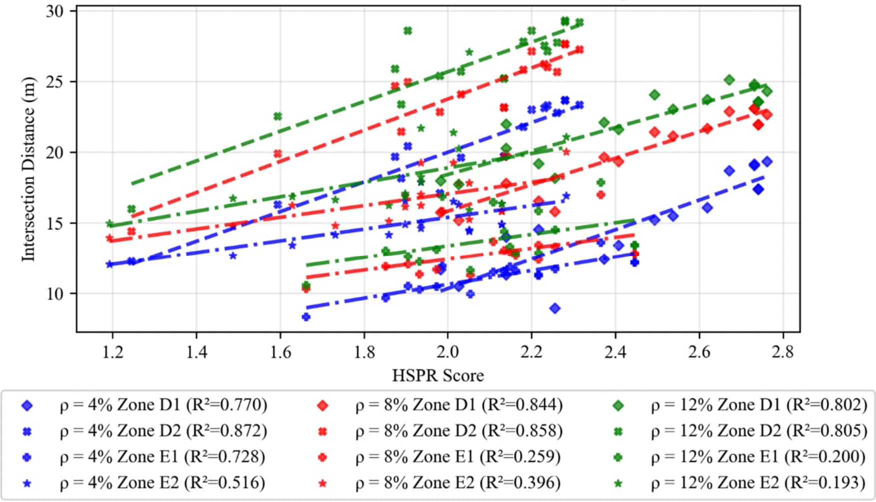

Figure 7 Mean of the three Iso-VL intersection distances over HSPR scores for Zones D and E, with each a nearside (numbered 1) and offside (numbered 2) with a VL target of 15 and varying reflection coefficients.

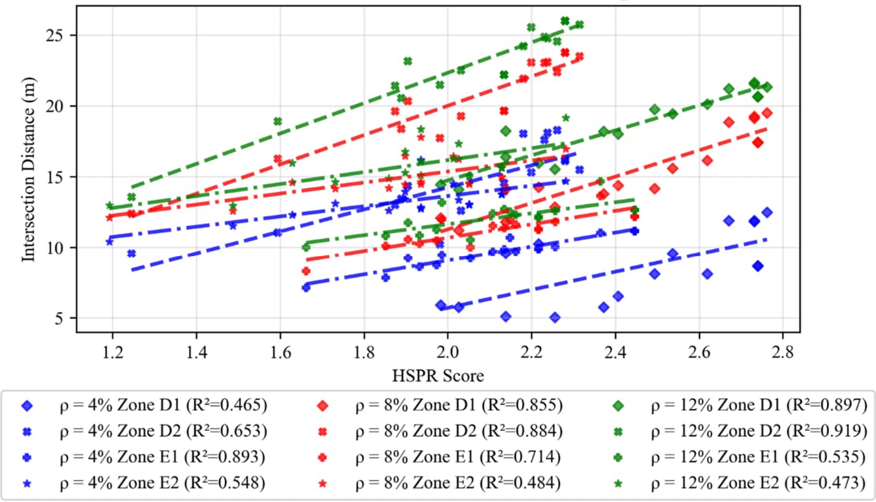

Figure 8 Mean of the three Iso-VL intersection distances over HSPR scores for Zones D and E, with each a nearside (numbered 1) and offside (numbered 2) with a VL target of 35 and varying reflection coefficients.

Conclusion

Because HSPR is a metric based on illuminances from 1 lx to 5 lx, it is independent of the reflective characteristics of objects and road surface’s reflection. This is a great advantage for generalization, for use by the lighting engineers and therefore for anything related to regulations. To obtain an accurate measure of human brightness and contrast perception, luminance and luminance contrast are required, which varies depending on surface characteristics. This investigation shows that even though HSPR does not take luminance into account, there is still a high correlation between its scoring system and the minimum requirements for object detection evaluated with the VL.

It has been demonstrated that an increase in HSPR scores results in a proportional increase in the detection distance for longitudinal distances greater than 30 m, regardless of the reflection coefficient between 4% and 12%. This, in turn, allows for an appropriate avoidance strategy when on a collision course with objects. An increase in HSPR therefore means a substantial improvement of the road safety.

For closer distances of 10 m to 20 m the estimation with the VL simulation lead to notable deviations between both metrics and in close proximity to the cut-off region a slight reduction in the correlation across various reflection coefficients and VL targets is notable.

For distances of 10 to 20 m, the estimation using the VL simulation resulted in significant discrepancies between the two metrics. In close proximity to the cut-off region, a slight decrease in correlation across various reflection coefficients and VL targets was evident.

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