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Summary This study evaluated changes in the light output of low-beam headlamps as a function of dirt accumulated during a 482 km route, representing a 10-day amount of driving for a typical United States driver. The complete route was traversed on three separate occasions, under each of the following environmental conditions: summer while dry, summer while wet, and winter with road salt. Candela matrices were obtained for a rectangular central portion of the beam, extending from 20° left to 20° right, and from 5° down to 5° up (in 0.5° steps). Photometry for each of two lamps was performed twice after the completion of each drive, first 'as is' and then after cleaning. The results indicate that dirt deposits tended to cause the light output to decrease below horizontal and increase near and above horizontal. The changes in the light output differed between the driver-side and passenger-side lamps, especially after the two summer drives. The largest changes occurred after the winter drive, with the decreases and increases in a large part of the beam for both lamps exceeding 25%, and with some of the increases exceeding 50%. At the United States, European and Japanese test points that control road illumination, the dirt effects tended to reduce the light output, and some of these decrements exceeded 25%. On the other hand, at test points that control glare, the dirt effects tended to increase illumination, but none of these increases exceeded 25%.

Low-beam headlamps: Effects of realistic levels of dirt on light output

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1 Introduction

Dirt deposits on headlamp lenses have two major effects: a reduction in the total amount of emitted light, and an increase in scattered light. The net effect is that, in many situations, the amount of light below horizontal (the light used for visibility) is reduced, while the amount of light above horizontal (glare light, as well as light needed for retroreflective traffic signs) is increased.

Past research has provided some indication of the magnitude of this problem. Relevant information concerning changes in the light output has been collected, for example, in the United Kingdom[1], Sweden[2], Germany[3], Yugoslavia[4] and The Netherlands[5,6]. This information indicates, for example, that decreases in intensity below horizontal can exceed 50%[1] and in some cases even 90%[2]. However, no comparable data exist for the United States.

The present study had three goals. The first goal was to obtain information relevant to the situation in the United States. The second goal was to obtain detailed information about the changes in a large portion of the beam pattern. In comparison, the previous studies provided information either about changes at a limited number of test points or about the locations of only certain isocandela/isolux curves. The third goal was to evaluate the effects of dirt on the light output at the current United States, European and Japanese test points.

Specifically, this study evaluated changes in the light output of low-beam headlamps as a function of dirt accumulated during a 482 km route, representing a 10-day amount of driving for a typical United States driver. The complete route was traversed on three separate occasions, under each of the following environmental conditions: summer while dry, summer while wet, and winter with road salt. Candela matrices were obtained for a rectangular central portion of the beam, extending from 20° left to 20° right, and from 5° down to 5° up (in 0.5° steps). Photometry for each of two lamps was performed twice after the completion of each drive, first 'as is' and then after cleaning.

2 Method

2.1 *Test vehicle*

A midsize car was used for this experiment. The car was equipped with its original headlamps (HB4s). The headlamps were clear lens, dual-reflector lamps with replaceable bulbs and faceted reflectors. Headlamp lenses were 160 mm wide and 96 mm high, with a 600 mm centre-to-ground distance. Centre-to-centre lateral separation between the two headlamps on the vehicle was 1 160 mm.

2.2 *Test route*

The test route was approximately 482 km long. It included roads in the southern and central portions of the lower peninsula of the state of Michigan. The surface of the route was asphalt (67%), concrete (30%), and unpaved (3%). In terms of the road type, the route included rural two-lane roads (53%), limited-access multi-lane highways (39%), and city streets (8%).

2.3 *Test conditions*

The test route was driven three times, each time during daylight hours on a work day. The first drive took place in June 1995, on a somewhat rainy and humid day. In terms of distance, about 18% of the drive involved wet roads and/or active precipitation.

The second drive took place in July 1995, on a hot, humid, sunny day, with many insects present in the air. No precipitation occurred during the drive, and the pavement was dry throughout.

The third and final drive was in January 1996, on a very cold day. Snow had fallen on a large part of the route within the previous 24 hours (but there was no active snowfall during the drive), and most of the route was heavily salted. Approximately 22% of the length of the route involved snowy or wet pavement (presumably with salt), 19% was classified as 'damp and salty', and 59% was mostly 'dry and salty'. The level of salt on the roads varied, but it was clearly visible on the road surface for over 80% of the route.

2.4 Test equipment

The measurements were made in a photometry laboratory, using a full-size height-adjustable goniometer. The distance from the headlamp to the measuring screen was 30 m.

2.5 Procedure

During the test drives, data were recorded for road condition, pavement type, weather, and mileage. Data were recorded every 5 minutes, or when the condition changed. The headlamps were turned on and off using the following repeated schedule: 64 km on, 32 km off.

The headlamps were cleaned at the beginning of each drive. At the end of the test route, the headlamps were removed from the vehicle. After their outputs had been measured in the 'dirty' condition, they were cleaned and the outputs were measured a second time.

Prior to photometry, the headlamps were placed in stands built specifically for their particular shape, and attached to the goniometer platform. Outputs were measured in 0.5° steps from 20° left to 20° right, and from 5° down to 5° up. Both measurements for one lamp (dirty and clean) were taken before the outputs from the other lamp were measured.

2.6 Evaluation of the effects of the changes in the beam pattern

Any decrease in the light directed towards the roadway and potential obstacles will contribute to a decrease in the visual performance of drivers. Similarly, any increase in glare light will result in reduced visual performance of the oncoming drivers. However, a nonzero criterion has to be established for evaluating the practical importance of light changes. For this study we selected a change of 25% as such a criterion. This selection was based on a finding that subjects require stimulus intensity to change by 25% for a noticeable difference to occur[7].

3 Changes in the light output throughout the beam pattern

3.1 Summer/wet

Percentage changes in luminous intensities from clean to dirty after the completion of the summer/wet drive are shown in Figure 1 for each lamp. For the left lamp, virtually all of the beam pattern below horizontal showed a decrease in luminous intensity. Conversely, virtually all of the beam pattern above horizontal showed an increase in luminous intensity. However, none of these changes were greater than 25%. For the right lamp, the decreases were confined to an area below about 2° below horizontal, with the remaining part of the beam pattern exhibiting increases. The changes that exceeded 25% were decreases in a small area centred around 4° below horizontal and 6.5° to the right of vertical, and increases near

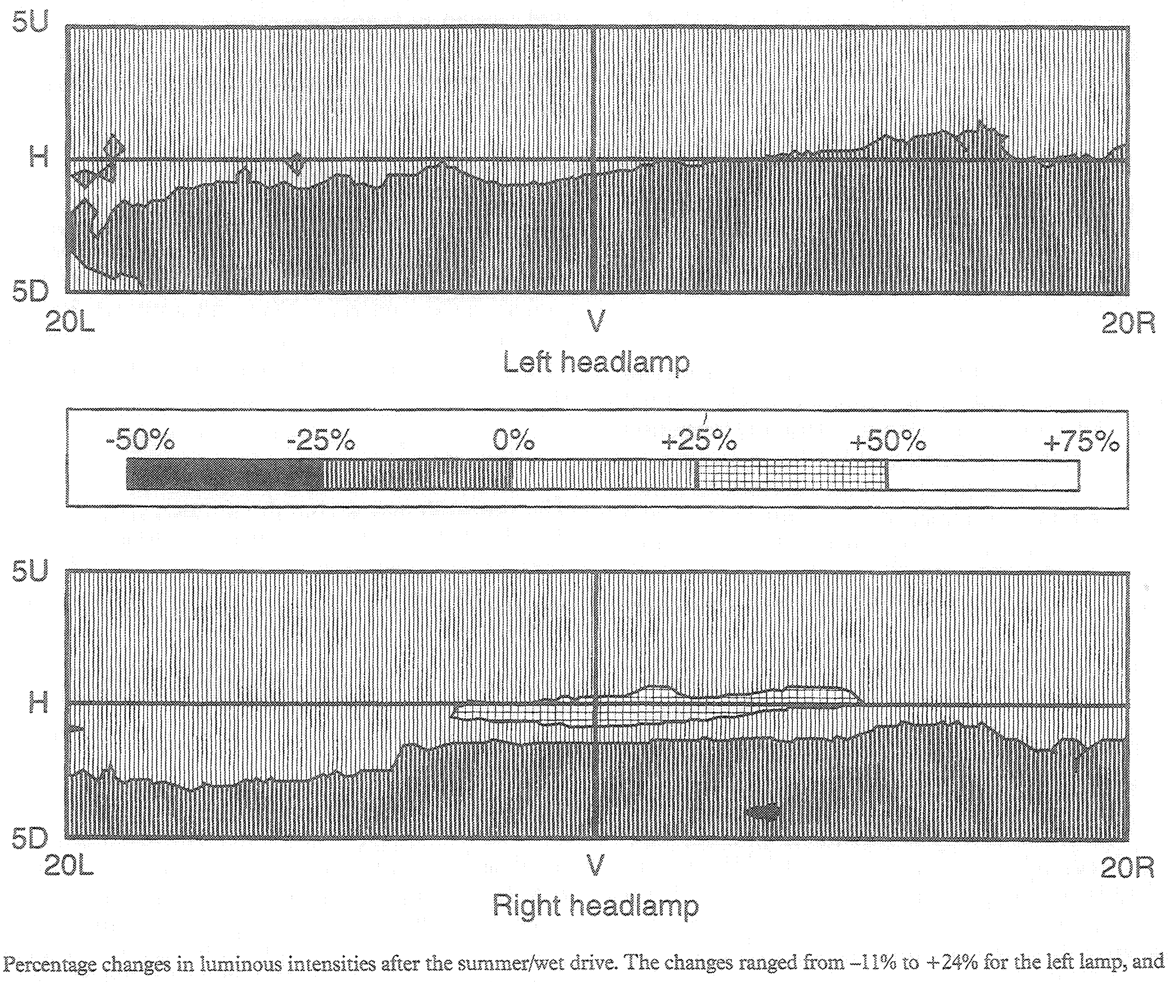

Figure 1 Percentage changes in luminous intensities after the summer/wet drive. The changes ranged from −11% to +24% for the left lamp, and from −28% to +49% for the right lamp.

horizontal from about 6° to the left of vertical to about 10° to the right of vertical.

3.2 *Summer/dry*

Percentage changes in luminous intensities from clean to dirty after the completion of the summer/dry drive are shown in Figure 2 for each lamp. The left lamp generally showed decreases in luminous intensity below horizontal and increases above horizontal. However, the changes were all within ±25%. For the right lamp the decreases were from 2–3° below horizontal to about 2° above horizontal. The other parts of the beam pattern tended to show increases. However, the only changes that exceeded 25% were the decreases just below horizontal (primarily from about 6° to the left of vertical to about 5° to the right of vertical).

3.3 *Winter/salty*

Percentage changes in luminous intensities from clean to dirty after the completion of the winter/salty drive are shown in Figure 3 for each lamp. For the left lamp, the decreases covered most of the beam pattern, except for an area above about 1–2° above horizontal. A large proportion of the changes were greater than 25%, with some of the increases (near 5° above horizontal) exceeding 50%. A similar pattern (with somewhat less extreme changes and with the decreases confined mostly below horizontal) was also present for the right lamp.

3.4 *Left lamp versus right lamp*

The magnitudes of the changes (both increases and decreases) after the two summer drives were greater for the right lamp than for the left lamp. On the other hand, the changes after the winter drive tended to be greater for the left lamp. It is possible that these differences are due to chance. On the other hand, it is also possible that these patterns are caused by more dirt being on the right side of the road during the summer months (attributable to the crown of the road). This speculative explanation assumes that the dirt present on the road in the summer is a product of longer-term accumulation, whereas the dirt in winter is somewhat more uniformly distributed across the width of the road because it includes recently applied salt. Alternatively, it is possible that in winter, with road salt and snow present on the road, splash from oncoming traffic contributes more to the dirt deposits on left lamps than on right lamps (for right-hand traffic).

4 Amounts and locations of greatest changes in light output

The magnitudes and locations of the largest decreases and increases in luminous intensities are shown in Table 1. The observed changes are expected to have substantial effects. For example, previous studies have shown that a 50% reduction in seeing intensity results in a reduction in seeing distance of between 10%[2] and 23%[3].

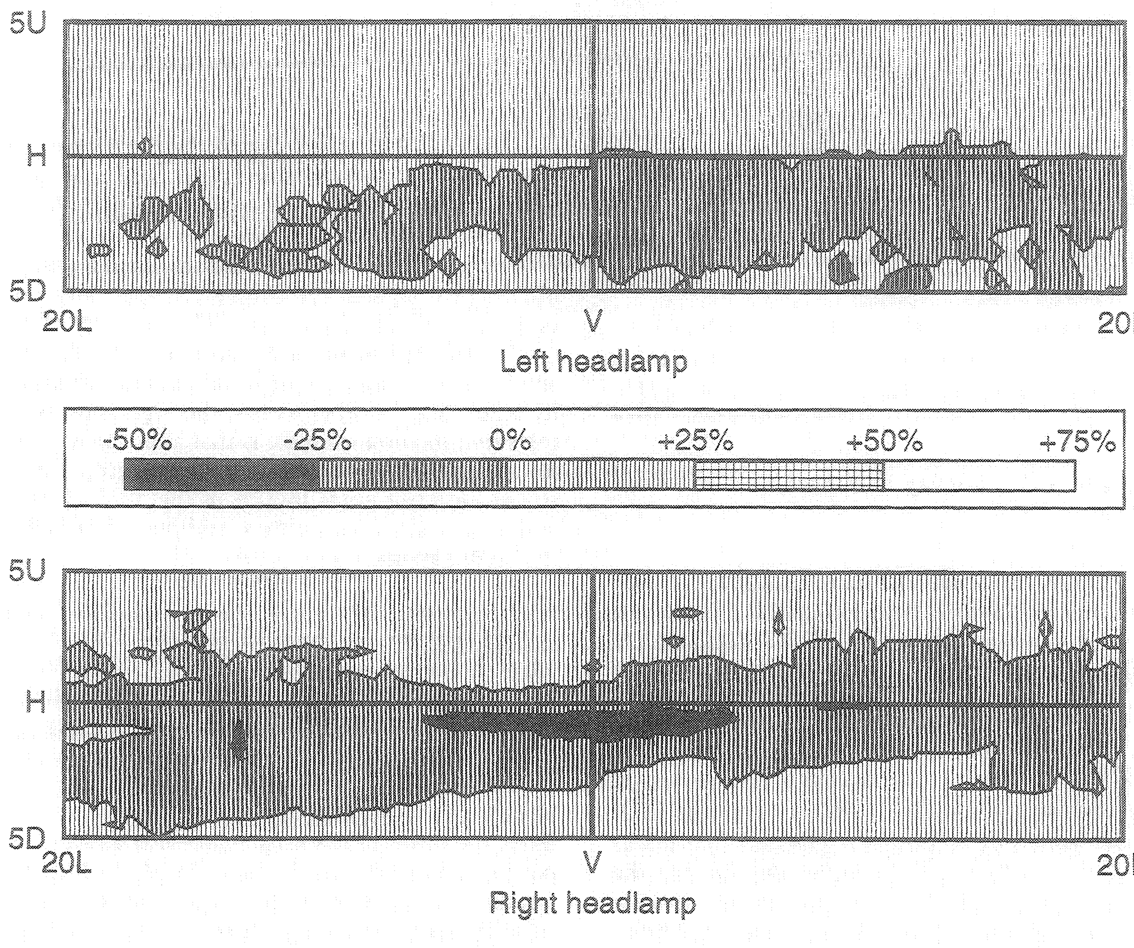

Figure 2 Percentage changes in luminous intensities after the summer/dry drive. The changes ranged from –5% to +15% for the left lamp, and from –36% to +24% for the right lamp.

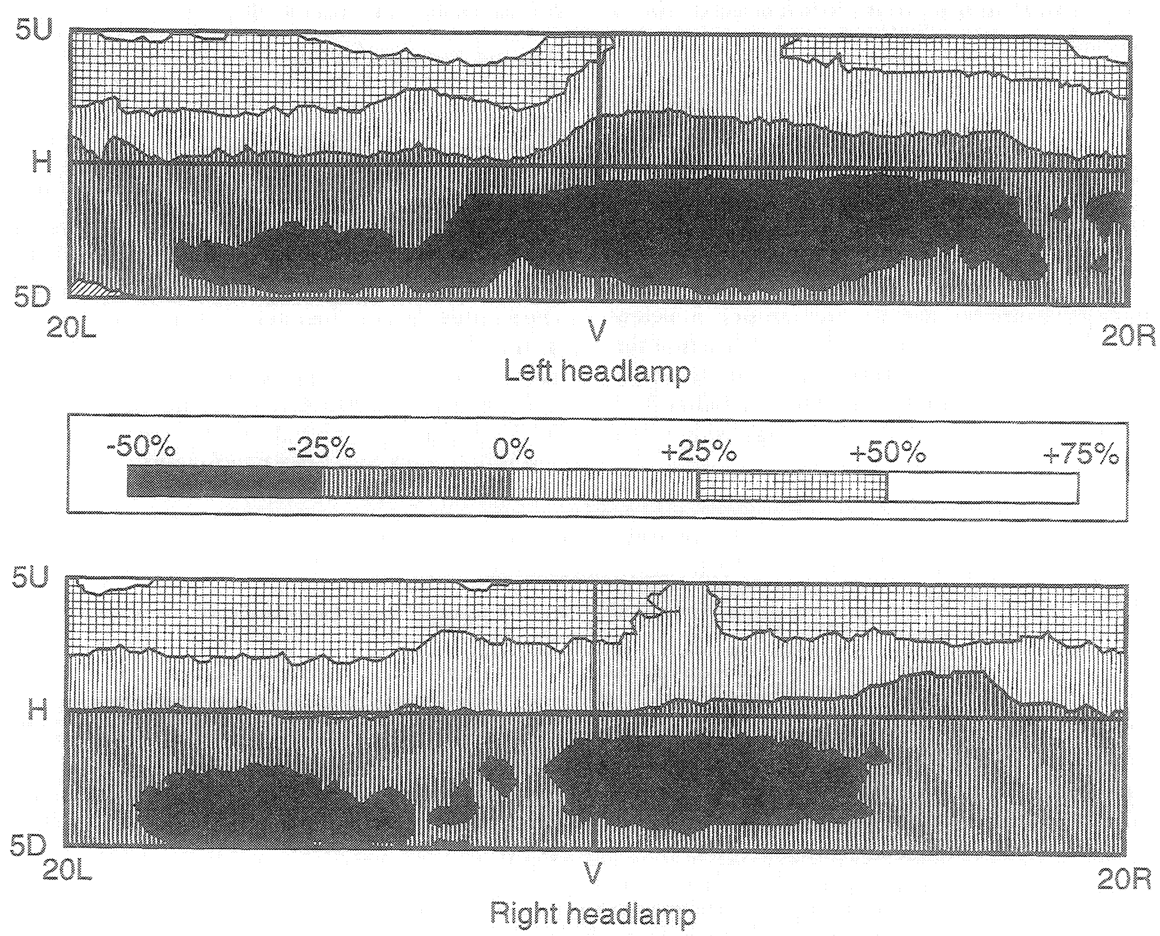

Figure 3 Percentage changes in luminous intensities after the winter/salty drive. The changes ranged from −35% to +66% for the left lamp, and from −31% to +55% for the right lamp.

Table 1 Magnitudes and locations of the largest percentage increases and decreases in luminous intensities

Largest change	Summer/wet		Summer/dry		Winter/salty	
	Left lamp	Right lamp	Left lamp	Right lamp	Left lamp	Right lamp
Largest decrease	11% at 3D, 4R	28% at 4D, 6.5R	5% at 1D, 18.5R	36% at 0.5D, 0.5R	35% at 1.5D, 4.5R	31% at 5D, 14L
Largest increase	24% at 5U, 6L	49% at 0.5D, 0.5R	15% at 5U, 5L	24% at 5D, 5.5R	66% at 5U, 5.5L	55% at 5U, 18.5L

5 'Clean' luminous intensity as a predictor of 'dirty' luminous intensity

Inspection of Figures 1 to 3 suggests that the effect of dirt, in general, was to increase intensities at points in the beam pattern that have low intensity when the lamp is clean, and to decrease intensities at points that have high intensity when the lamp is clean. This pattern of results can be formally described and quantified by regressing 'dirty' intensities on corresponding 'clean' intensities. The relationship between luminous intensities for clean headlamps and dirty headlamps proved to be reasonably well described by linear models (all r^2 values were 0.98 or greater). The fact that linear models provide a good first approximation implies that the effects of dirt can be modelled by two parameters: a slope (quantifying the degree of proportional reduction in the luminous intensity throughout the beam pattern), and an intercept (quantifying the amount of superimposed uniform intensity throughout the beam pattern).

An example of a scatter plot of the dirty versus clean luminous intensity for one lamp (right) and one environmental condition (winter/salty) is shown in Figure 4, along with a best fitting linear model. The slope of this equation (0.72 or 72%) is an estimate of the proportional reduction in luminous intensity throughout the beam pattern, presumably caused by both absorption and scattering. The intercept of this equation (112) is an estimate of the amount of the superimposed intensity (in cd) throughout the beam pattern, presumably caused by scattering. In other words, the regression equation indicates that the best estimate is that after the winter/salty drive for the right lamp, the dirt deposits reduced luminous intensity at each test point to 72% of the original value, coupled with a superimposed uniform addition of 112 cd throughout the beam pattern.

To the extent that linear regressions provide good first approximations to the relationships between 'clean' and 'dirty' luminous intensities, it can be estimated which levels of intensity will increase due to dirt and which will decrease. Using the best-fitting linear equations, the 'pivot' intensities were calculated. Luminous intensities of clean headlamps that are smaller than the corresponding pivot intensity would be expected to increase due to dirt, because at these intensity levels the uniform intensity increase is greater than the proportional decrease. On the other hand, the luminous intensities that are greater than the pivot intensity would be expected to decrease, because at these intensity levels the uniform intensity increase is smaller than the proportional decrease. (Points with luminous intensities equal to the pivot intensity are predicted to remain unchanged.) The specific calculation

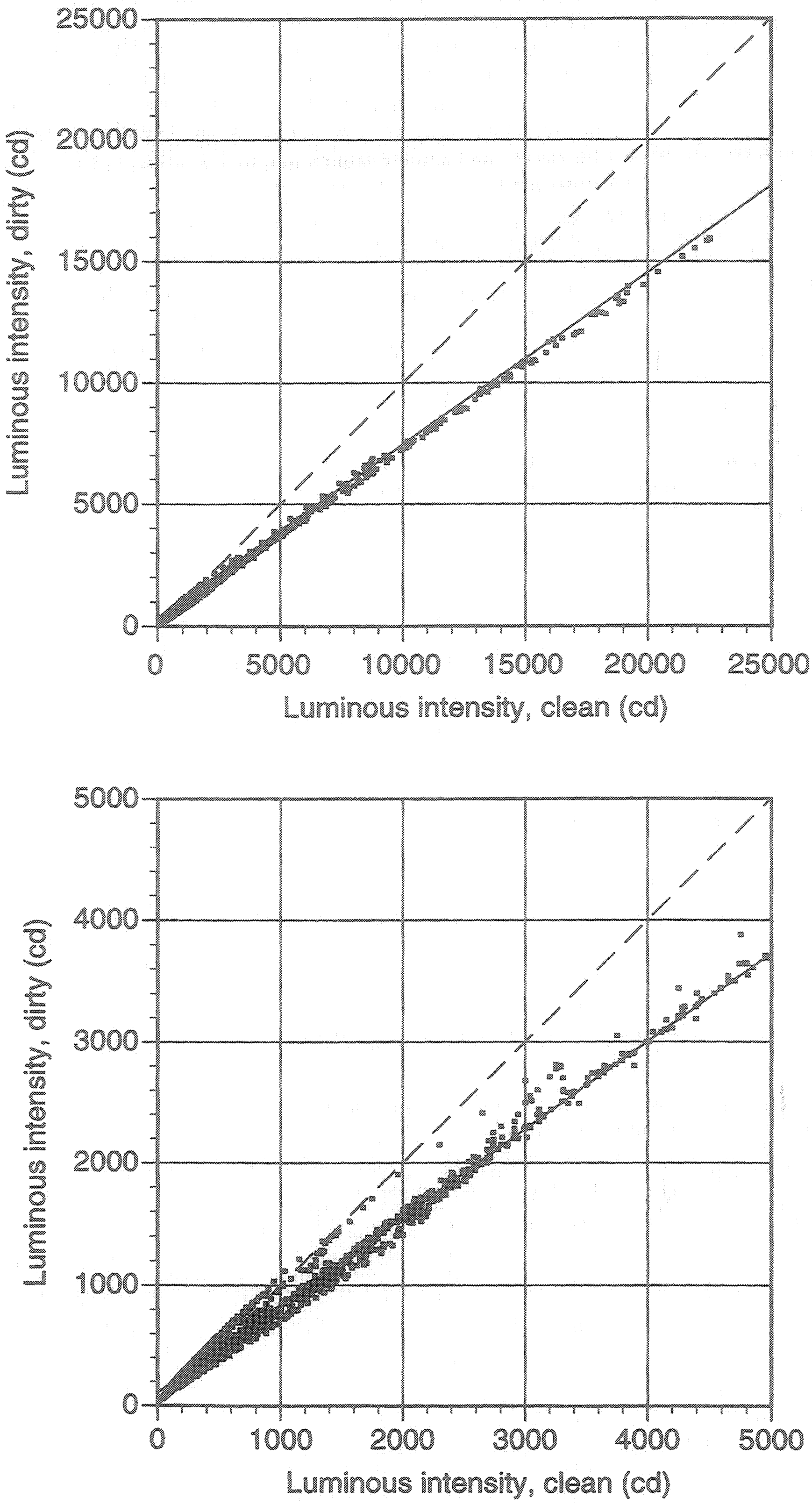

Figure 4 Relationship between the luminous intensities for the right lamp after the winter/salty drive. The solid line is the best fitting linear model ($y = 0.72x + 112$). For comparison, the dashed line shows where points would fall if intensities were unaffected by dirt ($y = x$). The top panel shows all 1701 test points. The bottom panel is an enlargement of the lower left portion of the data.

involved solving the regression equation ($y = ax + b$) for $y = x$. The pivot intensity for the example shown in Figure 4 (the right lamp after the winter/salty drive) proved to be 400 cd.

Although the overall fit of the model is very good, there appear to be some systematic departures from the predictions of the model. For example, for intensities that are very low (less than about 150 cd), the model predicted more of an increase than was the case — see the lower left corner in the bottom panel of Figure 4. Although the reason for this deviation is not clear, one possibility is as follows. By design, the low intensities are at the edges of the beam pattern — areas that are far from the brightest areas. It is likely that the amount of the superimposed intensity caused by scattering is not entirely uniform, but is instead reduced at greater distances from the bright areas.

It would be informative to run a similar study with lamps having different optical constructions (other types of United

States lamps or European lamps). Although our expectation is that the linear model would again account for large amounts of variance, any systematic deviations from the model would probably be instructive in further refining the model.

6 Changes in light output at the United States, European and Japanese test points

6.1 *United States test points*

Table 2 lists the changes in luminous intensities from clean to dirty after the completion of each drive at the current United States test points. The only consistent changes across both lamps exceeding 25% were present after the winter/salty drive at the following test points: increases at 4U, 8L (illumination serving primarily retroreflective traffic signs), and decreases at 1.5D, 2R (illumination for the right side of the road at about 23–29 m (assuming headlamp mounting height between 600 and 750 mm)), at 1.5D, 9R (lateral illumination for curves and intersections), and at 4D, 4R (foreground illumination).

6.2 *European test points*

Table 3 lists the changes in luminous intensities from clean to dirty after the completion of each drive at the current European test points. Again, the only consistent changes

Table 2 Percentage changes in luminous intensities for dirty lamps compared to clean lamps at the United States test points. (Entries in bold type indicate changes of at least 25%.)

Test point/	Summer/wet		Summer/dry		Winter/salty	
region	Left lamp	Right lamp	Left lamp	Right lamp	Left lamp	Right lamp
4U, 8L	15	20	8	7	43	35
4U, 8R	9	17	6	4	24	31
2U, 4L	10	13	11	5	22	18
1.5U, 1R to 3R	2	14	3	–3	–8	15
1.5U, 1R to R	2	17	3	–5	–8	12
1U, 1.5L to L	6	16	4	2	– 1	14
0.5U, 1.5L to L	4	17	2	–4	–9	9
0.5U, 1R to 3R	2	22	2	–14	–12	–2
H, 4L	5	27	4	–12	–4	–3
H, 8L	1	18	3	–12	–6	–1
0.5D, 1.5L to L	1	39	0	–32	–22	–19
0.5D, 1.5R	–2	41	–2	–33	–27	–21
1D, 6L	–3	9	–2	–22	–23	–23
1.5D, 9L	–2	6	0	–12	–21	–20
1.5D, 2R	–8	–4	–3	–13	–34	–29
1.5D, 9R	–9	–3	–2	–8	–32	–27
2D, 15L	–3	7	–2	–13	–21	–23
2D, 15R	–7	–5	–1	0	–26	–19
4D, 4R	–9	–22	–1	15	–29	–27

Table 3 Percentage changes in luminous intensities for dirty lamps compared to clean lamps at the European test points. (Highlighted entries indicate changes of at least 25%.) (Values interpolated from 5°C steps.)

Test point/	Summer/wet		Summer/dry		Winter/salty	
region	Left lamp	Right lamp	Left lamp	Right lamp	Left lamp	Right lamp
4U, 8L	15	20	8	7	43	35
4U, V	13	16	7	3	24	31
4U, 8R	9	17	6	4	24	31
2U, 4L	10	13	11	5	22	18
2U, V	4	13	5	1	0	20
2U, 4R	4	13	5	2	–1	19
H, 8L	1	18	3	–12	–6	–1
H, 4L	3	26	3	–13	–5	–5
0.57U, 3.43L	7	16	6	3	6	10
0.57D, 3.43L	2	29	–1	–30	–19	–21
0.57D, 1.14R	–2	35	–1	–33	–28	–23
0.86D, V	–3	23	–2	–34	–29	–25
0.86D, 1.72R	–5	18	–2	–31	–31	–27
0.86D, 3.43R	0	13	–2	–24	–24	–23
1.72D, 9L	–2	5	0	–12	–22	–21
1.72D, 9R	–9	–6	–2	–5	–32	–27
Zone 1†	–8	–8	–3	–6	–34	–29
Zone 3‡	4	31	0	–18	–16	–3
Zone 4§	–3	13	–1	–25	–24	–23

†1.72D to D.
‡Above line H, 20L; H, V; 5.36U, 20R; or above line H, 20L; H, V; 0.57U, 0.57R; 0.57U, 20R.
§Corners: 0.86D, 5.14L; 0.86D, 5.14R; 1.72D, 5.14R; and 1.72D, 5.14L.

Table 4 Percentage changes in luminous intensities for dirty lamps compared to clean lamps at the Japanese test points for four–lamp systems (converted to right–hand traffic). (Entries in bold type indicate changes of at least 25%.)

Test point/	Summer/wet		Summer/dry		Winter/salty	
region	Left lamp	Right lamp	Left lamp	Right lamp	Left lamp	Right lamp
1.5U, 1R to R	2	17	3	–5	–8	12
1U, 1L to L	6	16	4	2	–1	14
0.5U, 1L to L	4	17	2	–4	–9	9
0.5U, 1R to 3R	2	22	2	–14	–12	–2
0.5D, 1L to L	–2	16	–2	**–30**	**–28**	–23
0.5D, 2R	–3	**37**	–1	**–31**	**–28**	–22
1D, 6L	–3	9	–2	–22	–23	–23
1.5D, 2R	–8	–4	–3	–13	**–34**	**–29**
1.5D, 9L	–2	6	0	–12	–21	–20
1.5D, 9R	–9	–3	–2	–8	**–31**	**–27**
2D, 15L	–3	7	–2	–13	–21	–23
2D, 15R	–7	5	–1	0	**–26**	–19
4D, 4R	–9	–22	–1	–15	**–29**	**–26**

across both lamps exceeding 25% were all present after the winter/salty drive. These changes were as follows: increases at 4U, 8L (serving primarily retroreflective traffic signs; the same test point as in the United States), and decreases at 0.86D, V (illumination of the centre of the lane at about 40–50 m), at 0.86D, 1.72R (illumination for the right side of the road at about 40–50 m), at 1.72D, 9R (lateral illumination for curves and intersections), and in Zone 1 (foreground illumination).

6.3 *Japanese test points*

Table 4 lists the changes in luminous intensities from clean to dirty after the completion of each drive at the current Japanese test points (converted to right-hand traffic). As was the case for the United States and European test points, the only consistent changes across both lamps exceeding 25% were all present after the winter/salty drive. Furthermore, they were all decreases, and they all occurred below horizontal. These test points (all in common with the United States test points) were as follows: 1.5D, 2R (illumination for the right side of the road at about 23–29 m), 1.5D, 9R (lateral illumination for curves and intersections), and 4D, 4R (foreground illumination).

6.4 *Changes at test points controlling visibility, foreground, and glare*

As is evident from the above discussion, all of the consistent changes for both lamps were after the winter/salty drive, and they were all at test points controlling either visibility (both below and above horizontal) or foreground. The changes at the primary test points that control glare for the oncoming drivers (0.5U, 1.5L to L in the United States and Japan, and 0.57U, 3.43L in Europe) did not reach 25% for either lamp in any of the environmental conditions.

7 Conclusions

The results indicate that dirt deposits tended to cause the light output to decrease below horizontal and increase near and above horizontal. The changes in light output differed between the driver-side and passenger-side lamps, especially after the two summer drives. The greatest changes occurred after the winter drive, for which the decreases and increases in a large part of the beam for both lamps exceeded 25%, and some of the increases exceeded 50%. At the United States, European, and Japanese test points that control road illumination, the dirt effects tended to reduce the light output, and some of these decrements exceeded 25%. On the other hand, at test points that control glare, the dirt effects tended to increase illumination, but none of these increases exceeded 25%.

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Discussion

J Cobb (VisualEyes)

Congratulations to Sivak *et al.* on a very interesting and informative paper, particularly the investigation of the whole beam pattern. My comments seem like criticisms, but are really a thirst for more knowledge. I want to know what the results mean, and if it's bad news, what might be done about it.

The title of the paper mentions 'realistic levels' and explains that the dirt was collected by driving 482 km, representing 10 days driving. Is this the average interval between cleaning for US drivers? The Transport Research Laboratory measured the effect of realistic levels on all lights by stopping vehicles at the side of the road[8], and found output reduced by 30 to 50%, with headlight glare increased by up to 50% for 'very dirty' lights.

This study used three weather conditions. However, the wet part appears to have been wet for only 18% of the distance. Presumably the headlights were allowed to dry before their output was measured, so the results represent what happens after, rather than during, rain or snow. Was there any difficulty in the cleaning, particularly the insects caught during the dry summer? Could the effects of the dirt have been eliminated by the use of headlight wash/wipe? Why were the headlights switched on for some of the journey?

In section 2.6, 25% is selected as being a criterion of no change. I would not dispute that drivers would not notice a smaller change, but in the case of glare this represents only discomfort glare. The more important disability glare may be occurring without the driver being aware.

The differences between left/right headlights are interesting and, as far as I am aware, new information. I can believe the speculative explanation of this and the differences with snow offered in section 3.4.

Section 5 shows an interesting model of the effect of dirt. The 400 cd pivot point is close to the average glare level found in the UK. The suggestion about the very low levels is plausible, and would affect E-beams more, with their sharper gradient between bright and dark parts of the beam.

Mention is made several times of increased light towards retro-reflective signs, but presumably these will also be affected by the weather so that increases in light due to scattering from the headlights may be lost by reductions in reflectivity.

Reference

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Authors' reply to discussion

We appreciate the discussor's kind words and thoughtful questions with regard to our paper.

We are not aware of any data on the average interval between car washes (or headlamp washes) in the United States. The phrase 'realistic levels' is meant to refer to realistic levels after ten days' worth of driving without car/headlamp wash. Although the experimental method used here does not allow a complete estimate of on-the-road dirt levels, it allows a better evaluation of the effects of the various weather conditions than would be possible with a survey of naturally occurring dirt levels.

In the summer/wet condition the headlamps were in fact allowed to dry before they were tested. We did not have any difficulty cleaning the lamps, even in the summer/dry condition. It is quite likely that the effects of dirt would have been substantially reduced by the use of headlight washers/wipers. The headlamps were switched on for $^2/_3$ of the distance so that the lens would be at the relatively high temperature characteristic of those times, during nighttime and low-visibility driving, when the headlamps are normally switched on. The temperature of the lens is likely to influence the nature of dirt deposits.

As we indicated in section 2.6, we agree that visibility changes will begin to occur at illumination changes of less than 25%, and we agree that disability glare is more important than discomfort glare. Although discomfort glare and disability glare are not the same things, they are strongly enough related that we do not think it unreasonable to apply a criterion from discomfort glare to disability glare. Clearly, any such criterion must be considered tentative, and the justification for it must be made explicit, as we have tried to do in section 2.6.

It is possible that in some situations the increase in the illumination directed towards retroreflective traffic signs might be compensated for by effects of weather on the signs themselves. However, for purposes concerning the design or maintenance of headlamps, the relevant comparison involves keeping the sign condition the same, while varying the presence or absence of dirt on the headlamps.