O Say, Can You See?

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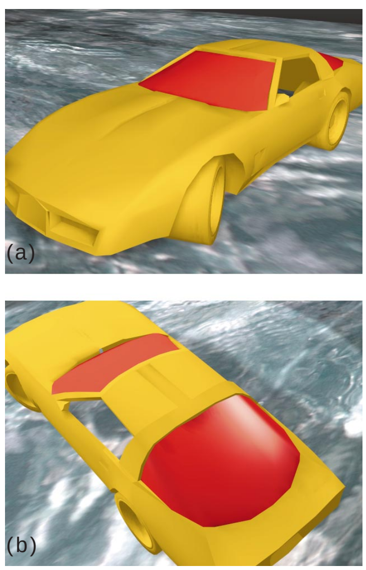
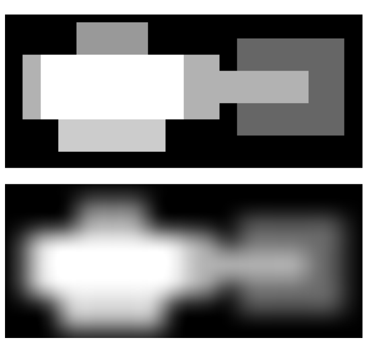
I like the sound of rain. That's a good thing, because in the Pacific Northwest we get plenty of it. We spend a lot of time driving our cars and trucks in the rain, straining to see the road and the rest of the world through the splattered water on our windshields.

While riding a bus recently during a rainy trip, I thought about how much rain was striking the big windshield and what a tough job the windshield wipers had keeping it clean. I conjectured that different designs of windshield wipers would work with differing degrees of efficiency. I don't know anything about how car designers really design windshield wipers, but I decided to try some reverse engineering and compare different designs.



1 A Corvette with windshields highlighted. Notice the shape of the windshields: (a) from the front and (b) from the top.



2 My plot of D, the driver's windshield importance, seen from inside the car. The driver sits on the left, the passenger on the right. (a) The importance plot. Lighter means more important. (b) A blurred version.

I see you

To compare the efficiency of windshield wipers, we need to decide what we mean by efficiency, and then decide how to measure it. I'm going to take a very pragmatic approach, motivated by personal observation. When I try to look through my windshield, I'm mostly bothered when there's a lot of rain right where I'm trying to look. So some parts of the windshield matter more than others—a good wiper design keeps the important parts of my windshield dry.

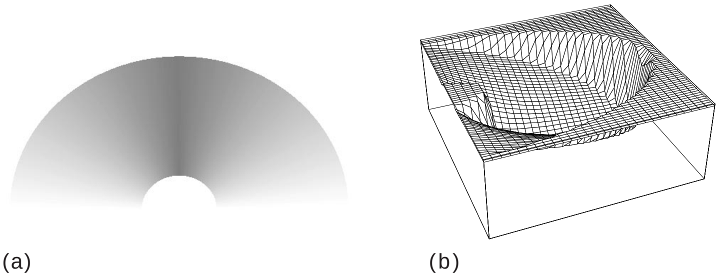
To measure a wiper pattern, I'll first establish what parts of the windshield matter to me. Then I'll figure out the pattern of the wipers and see how good a job they do at keeping the important areas clean.

To begin, let's look at a windshield. Figure 1 shows a Corvette model that comes with 3D Studio Max. I painted the car a flat color but highlighted the front and back windshields. Notice that the front windshield looks something like a trapezoid curved back in 3D. This would be a tough shape to simulate directly, but just using a flattened trapezoid distorted the geometry of the wipers. So I decided to treat my windshields in this column simply as rectangular, flat pieces of glass. Notice from the overhead view in Figure 1b that this approximation looks even worse for the back window of a Corvette.

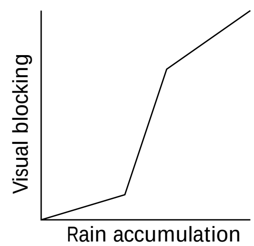
Of course, it's not a bad simplification for all cars. Planar windshields were standard in early cars such as the Pierce-Arrow and early Fords. You can still see that design today—I recently saw a current Brink's armored car, and the windshield was a wide, short, flat rectangle.

Now we need to decide on the importance of the different regions of the windshield to the driver. It's more critical that the driver can see the road directly in front than some detail near a far edge of the window. Figure 2 shows my personal assessment. Here, we're looking through the windshield from the inside of the car, so the driver is looking out the left side, and the passenger sits on the right side. I weighted each region by the amount of importance I've assigned it.

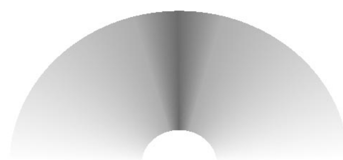
The region right in front of the driver seems the most important, so I've given that a weight of 1. The regions to the left and right help the driver see other cars for lane changes and pedestrians at intersections; I sketched out regions for those and weighted them 0.7. Next, we want to avoid obstacles on the road itself, so the region under the central view must be clean; I gave it 0.8. I don't usually have to dodge many helicopters when driving, but I do need to see the overhead traffic lights. Those lights are so big and bright that I can still make them out



3 **The single-wiper pattern S, indicating the maximum rain accumulation over one cycle of the wiper. (a) Dark means no accumulation at all, light means one full cycle's worth. (b) A height plot. The higher the value of the graph, the more rain that accumulates at that spot over a single wiper cycle.**



4 **My curve B that relates rainfall density to view blockage.**



5 **B(S). This tells how much the rainfall density bothers the driver.**

6 **The cost pattern $C_S = D \times B(S)$. This results from weighting the wiper density, then scaling each point by the driver's windshield importance.**

despite a lot of rain, so keeping that region clean is just a convenience; I gave it a weight of 0.6. Finally, I blocked out a nice view for the passenger and weighted that 0.4. Everything else can get as rainy as it wants, so I've given it a score of 0.

Because such hard-edged boundaries look too artificial, even for something like this, I blurred the importance diagram in Figure 2b. This is the pattern I'll actually use for evaluating the quality of wiper designs. I call it D, since it represents the driver's criteria for good visibility across the windshield.

I'll use these weights to determine how well the wiper design works. A good design should clean the high-value regions and not waste a lot of effort in regions with low importance.

The one-blade arc C

Figure 3 shows my first wiper design: a single blade running in a big arc from one side of the windshield to the other. The pivot of the blade lies just below the windshield itself. I modeled this pattern after the wiper on the back of my car. Some Mercedes-Benz models have a wiper like this on the front windshield, moving at very high speed. As I mentioned before, the central question for me is how much rain I have to look through to see the world. Rather than measuring the average amount of rainfall on the windshield, I'd rather measure how bad it can get.

On a point-by-point basis across the windshield, I'll compute how much rain can accumulate in the worst case before the wiper cleans it off. For convenience, I'll assume that the wiper takes one second to complete a cycle—that is, swishing from one end to the other, then back again. So the bits of the windshield at the ends of the arc only see the wiper once a second. In other words, a whole second elapses before they get wiped clean. A point in the middle of the arc, though, gets wiped every half second.

In Figure 3a, I scaled the time interval [0, 1] to the gray scale [0, 255]. Notice that wiper never gets to the upper left or upper right corners of the windshield, so a full second of rain accumulates there. If you think of the rain as snow, whiter pixels means more snow has built up. To help lock this down, Figure 3b shows another view of the wiper pattern as a height field. Light regions in the grayscale figure have high values in the height plot, representing the accumulation of the maximum amount of rain over one wiper cycle. I'll represent this wiper patterns with the label S.

A little thought reveals that the maximum accumulation along the wiper's arc between visits drops off along the arc, linearly with the angle (see Figure 3).

Now, how does this relate to rain? I'll assume that the rain falls uniformly over the surface of the windshield and over time. So the amount of rain falling on any spot linearly relates to how long it's been since that spot has been wiped. I'll assume that the rain density is 1 in some convenient set of units. That means that we can now interpret the time plot of Figure 3 as a rain buildup plot over the period of one second.

Now that I've shown that Figure 3 indicates rain buildup, I'd like to add another step. A little mist isn't really much of a problem, nor is a drizzle. The effect of the rain on visibility is nonlinear. It doesn't matter much until the rain starts to fall pretty hard, then it starts to matter a lot. To model this, Figure 4 shows my take on the curve that relates visibility to rainfall. I'll call that B.

If we pass S (in Figure 3) through the function B (in Figure 4), we get B(S), shown in Figure 5. This now tells us on a point-by-point basis how bad visibility is across the windshield for this wiper. The last step combines this with the importance diagram D in Figure 2 to determine how well this wiper works.

I'll simply multiply these together, forming the cost pattern, $C_S = D \times B(S)$, shown in Figure 6. The lightness of a pixel represents how much of a toll it takes on our visibility: to be colored white, a pixel must have high importance and receive a lot of rain over each wiper cycle. Figure 7 shows another view of C_S, where I mapped the range from black to white into the range blue to yellow. Since some of the other patterns are very dark, I'll use this color range to illustrate the rest of the cost patterns as well.

What does the world look like through a windshield as it's cleaned by this wiper? Since we're driving through rain, it seems only natural to plunge into the ocean and head for a coral reef, such as the one shown in Figure 8. I'll assume that this is the scene in front of the car and that this is how it would look on a dry day (underwater, of course).

Figure 9 shows my approximation to the view of Figure 8 under wiper pattern S. The basic assumption is that rain causes things to get kind of smudgy and blurry. Actually, each raindrop acts like a small magnifying lens, but a blur seemed like a reasonable approximation of the cumulative effect of many drops, particularly after they streak and run together.

To create Figure 9, I convolved the reef image with a variable-radius conical kernel. In practical terms, this means I built a cone centered over each pixel of Figure 8 and scaled its radius by the unweighted accumulation value in Figure 3. Then I added up all the pixels under the cone—each weighted by the height of the cone at that point—divided by the total of the weights, plunked the result into Figure 9, and moved on to the next pixel. The result is an image that looks smeary or blurry where a lot of rain has accumulated and appears sharper where the rain gets washed away more frequently.

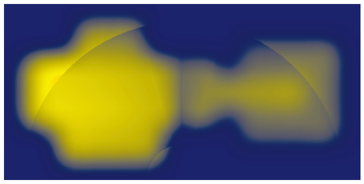
Note that this picture isn't a snapshot of any given moment, but rather a kind of general worst-case image. In other words, the fuzzy areas are likely to appear fuzzy most of the time, the clear areas clear most of the time.

To compare this wiper pattern with others, I'll simply add up all the pixel values in the cost pattern and divide by the number of pixels in the image to get a score S. The score for this pattern is $S_S = 75.8$. The higher the score, the worse the result because the score adds up all the costs of having our view blocked. We'll aim to find patterns that have low scores.

How might we improve on this score? It seems to me that if we split the wiper into two pieces, each piece would only need to cover half the arc. If we use the same motors, moving the blades at the same speed, each point would be visited twice as often. In other words, two blades forming a V shape sweep together.

I'll call this pattern S2, meaning a single arc with two blades. Figure 10 shows the diagrams S2, B(S2), the colored version of C_{S2}, and the image of the reef. The score for this pattern is $S_{S2} = 27.5$. That's almost a factor of three improvement.

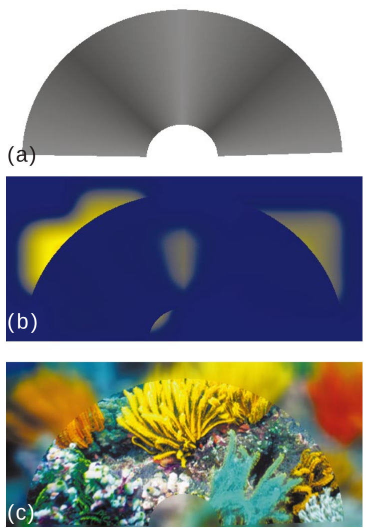
Well, if one is good, and two is better, then by induction a gazillion must be terrific. The best windshield wiper of all would be a solid block of rubber that covered the windshield, so dense that it never needs to move. According to my model, it would have a perfect score: 0. This is another example of why you don't want to trust computer models too much, unless you know exactly what's inside them. The flaw in my model is obvi-



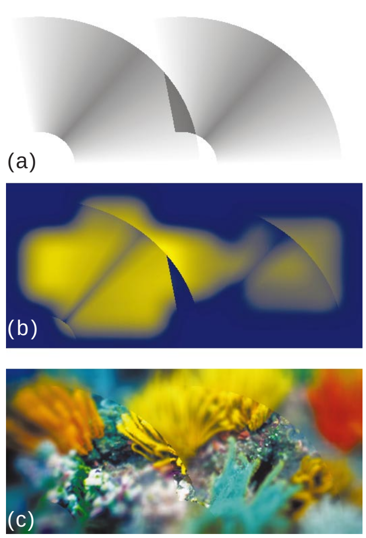
7 **The cost pattern C_S in Figure 6, with black mapped to blue and white to yellow.**

8 **A coral reef, representing the perfect view out of your windshield on a clear day.**

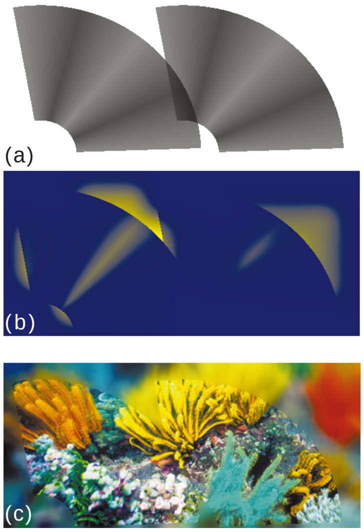
9 **The view of the coral reef through wiper pattern S.**



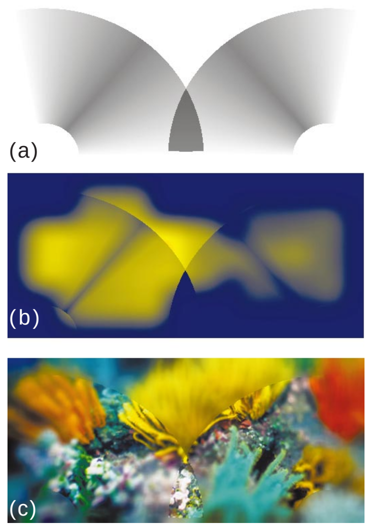
10 **The diagrams for the two-bladed single arc, S2. (a) The wiper diagram S2. (b) The cost diagram C_{S2} representing $D \times B(S2)$. (c) The view of the coral reef.**



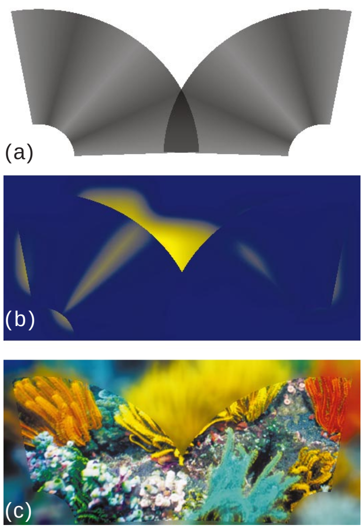
11 **The diagrams for the two-arc pattern T. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.**



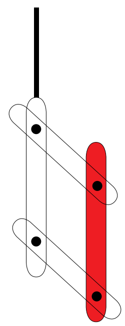
12 The diagrams for the split two-arc pattern T2. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



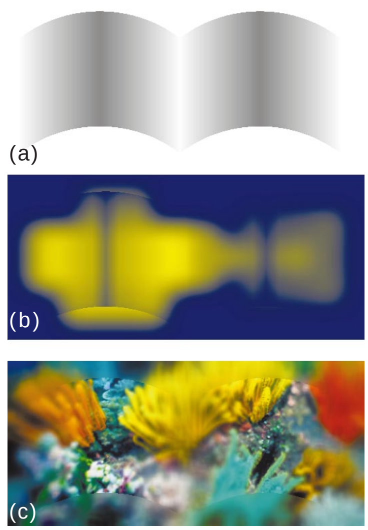
13 The diagrams for the two-arc pattern M. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



14 The diagrams for the split two-arc pattern M2. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



15 The four-bar linkage for a vertical wiper. All four dots represent freely rotating hinges. The red bar is fixed in place to the chassis. As the other links move, they always form a parallelogram. The black bar at the top represents the wiper, which moves in an arc, but stays vertical.



16 The diagrams for the two-linkage pattern L. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.

ously that I'm not factoring in the effect of obscuring the driver's view with the wiper itself. Even the two-bladed design in Figure 10 might be too much for practical use, but I haven't tried it out.

The two-arc pattern T

The front windshield of most cars gets swept clean by two wipers that move in synchrony: When one is fully clockwise, so is the other. Like the single blade, they pivot from beneath the windshield.

Figure 11 shows the version that's on my car, a 1984 Toyota Tercel. Calling this pattern T, it results in the score $S_T = 71.3$. We can play the same game as we did before and split each wiper into a V-shaped pair, as Figure 12 shows. The score is $S_{T2} = 24.9$.

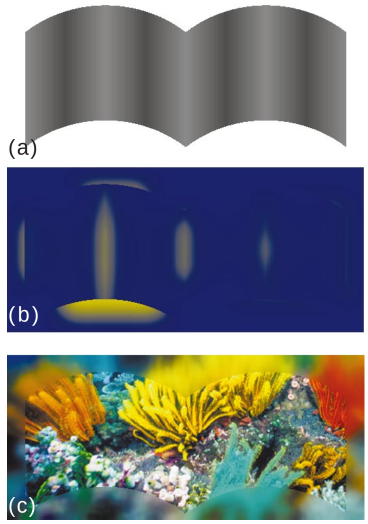
The two-arc pattern M

Figure 13 shows another way for two wipers to move, illustrating pattern M. The two wipers move opposite to one another: when one is rotated fully clockwise, the other has rotated fully counterclockwise. The score for this pattern is $S_M = 71.6$. If we split each wiper into a V-shaped pair, as Figure 14 shows, the score is $S_{M2} = 25.8$.

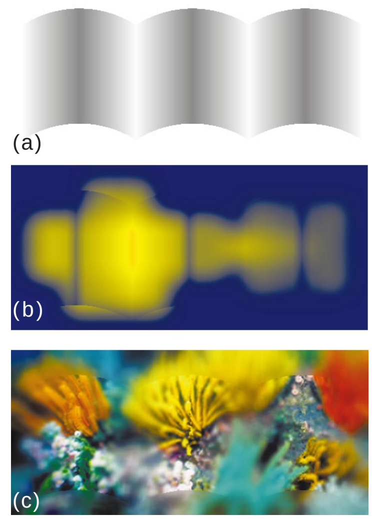
The four-bar linkages L and P

The windshield wiper that inspired this column is used on many buses and trucks. It's based on a four-bar linkage, as shown in Figure 15. One point of the linkage is locked down. By moving the other bars, Figure 15 maintains a parallelogram. If a wiper blade is attached to one of the vertical bars, the blade moves from left to right, rising up in the middle along a circular arc. The blade itself always stays vertical.

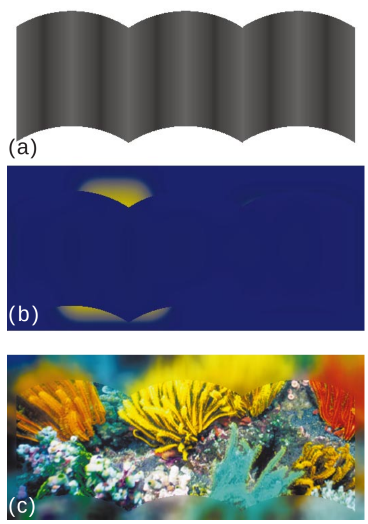
Figure 16 shows the diagrams for the pattern generated by this approach; the score is $S_L = 74$. If we split each



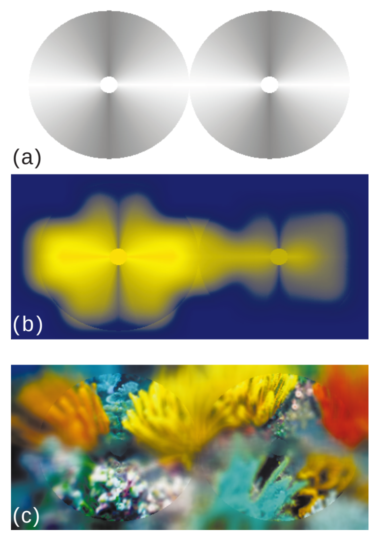
17 The diagrams for the split two-linkage pattern L2. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



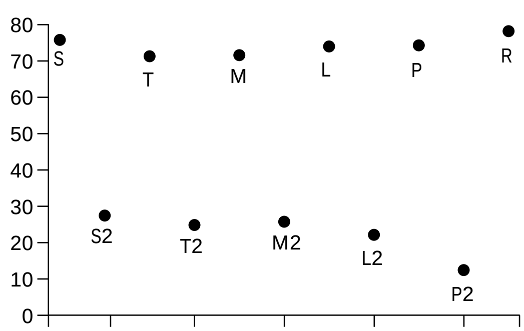
18 The diagrams for the three-linkage pattern P. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



19 The diagrams for the split three-linkage pattern P2. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



20 The diagrams for the radar pattern R. (a) The worst-case accumulation. (b) The wiper performance. (c) The view of the coral reef.



21 A summary of the scores for the various patterns.

wiper into a pair of side-by-side blades, as Figure 17 shows, the score is $S_{L2} = 22.2$.

Since this pattern does so well, what if we split the pattern in three pieces? Of course, we can get obscuration problems again, but let's just see how clean the windshield gets. Figure 18 shows the result—the score $S_P = 74.3$. Splitting these (for a total of six blades) as in Figure 19, the score is a terrific $S_{P2} = 12.5$.

The radar screen R

Just for fun, I thought I'd take a stab at a wiper design that looked like a radar screen. Figure 20 shows the idea and the results. Each circle consists two 180-degree arcs, one on the top half and one on the bottom. You may have noticed that there's a small problem here. We'd need to mount a motor (or at least a mechanical gadget) smack in the center of the field of view. Another problem might be in the practical aspects of the lower blade as it gets above about 45 degrees: then it might be effectively pushing a little wall of water vertically up the windshield. The score for this pattern is $S_R = 78.2$.

Summary

Figure 21 shows a summary of the scores for the windshield wipers we've looked at here, plotted left-to-right in the order of discussion. Keep in mind that I'm not accounting for the view blockage caused by the wipers themselves, and I approximated the interesting, curved windshield with a flat rectangle.

Looking over the scores in Figure 21, it's pretty clear that the peformance of most of the single-blade designs is roughly similar, as are most of the double-blade designs. The standout is the pattern P2, but that has six separate blades whizzing along at once, which is probably too much for any practical situation.

It's not clear that any of the double-blade designs are mechanically practical. I think that they might pose some tricky engineering problems and increase the cost of the car. I've also neglected the practical problems of the friction between the blade and the glass and the torque required from the motor for the different designs. These might also affect the practicality of some patterns.

The interesting thing to me is that the results here seem roughly consistent with what's actually being manufactured, even though I only eyeballed the wiper patterns and modeled them on a flat rectangular windshield. Assuming that you only want to have one wiper blade moving in front of each person, then the T and M designs score best under this analysis. These are by far the ones I've seen most often on the road on passenger cars.

Some boats that go out on the high seas use a completely different kind of approach to keep their windshields clean, bypassing wipers altogether. A rectangular hole cut in the center of the windshield holds a frame containing a clear disk. The frame consists of some strong, opaque material, while the disk itself is transparent. While at sea, the disk spins at very high speeds. When water strikes it, the centrifugal force flings the water out and away from the disk, where a series of baffles channel it out into the ocean. The disk itself is almost never obscured by water on its surface. This is very efficient. In terms of our scores, it would be nearly zero because the water never has a chance to build up at all.

Although this design seems to work well for boats, I'm guessing that it's overkill for most cars, both in efficiency and cost.

I found a couple of links with pictures of the *Amphicar*, a car that can drive on normal roads, but also in water like a boat (http://www.geocities.com/MotorCity/1186/ and http://www.avonlogic.com/acarint.htm). It looks like the Amphicar has the T-type wipers in Figure 11. This suggests that this is the most inexpensive and reliable design for automobile wipers, on land or sea. ■

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