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Research on the Possibility of Camouflaged A-pillars by Using the Quadrangular Prism of Self Invisibility

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Abstract A novel method to camouflage A, B, C and D pillars of vehicles by using quadrangular prisms of self invisibility has been proposed and is being researched. After comparing with some existing technologies of A-pillar designs which attempt to reduce the area of the blind spot, the effectiveness of the quadrangular prisms and the geometrical and mechanical characteristics have been investigated quantitatively through the concrete size of the driver's seat of a Lexus. The analyses clearly show that the stealth effect for the A-pillars of trucks and jeeps will be much better than that of cars because of the sharper incline of the A-pillars in trucks and jeeps. The main disadvantage, the sensitivity of the invisible rate with respect to the changing positions of the driver's eyes due to the varied heights of drivers, was analysed and then some attempts to overcome such a drawback were tentatively suggested.

Keywords: *stealth technology, camouflage technology, automobile industry, A-pillar of vehicle*

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1. Introduction

Camouflage technology has already been well developed, particularly in military industry. Aircraft can be easily concealed if the plane can prevent electromagnetic waves radiated from radar from returning back to the radar itself. Otherwise, based on the reflected signals, the position information of aircraft will be located precisely by observers [1-8]. Similarly, bats emit squeaks and by receiving the echoes, they can locate and steer clear of obstacles or locate flying insects on which they feed.

In contrast, stealth technology for wavelengths of visible light is rarely used in daily life due to security and practical difficulties.

Objects will be directly camouflaged when the light signal emitting or bouncing from any object fails to reach the observer's eye. Therefore, research for stealth technology focuses on how to bend light away from the observer efficiently. It is obvious that two approaches, the refractive and reflective, are essential to directly bend light. Although the principle of stealth is quite simple, the practical use is another thing, because several concrete problems concerned should be considered seriously. As we know, there are several approaches to camouflage some objects, larger and small in size, in the light of the law of light refraction and reflection. No matter which way is adopted, the outer materials, refractive covers or reflected mirror, are inevitably utilized; otherwise, the light cannot be bent to escape from the observer's eye.

A novel approach, without depending on any any refractive or reflective outer materials, was first invented [9] and some further research has been done [10,11]. In this paper, one essential application---to replace traditional A-pillars in vehicles---is considered both qualitatively and quantitatively, after comparison with some typical existing stealth technologies. The main defects of this device are pointed out and some possible strategies to overcome them are tentatively suggested.

2. Some Existing Inventions to Make Objects Invisible by Light Reflection

i) Parabolic mirror or plane mirror to camouflage

A camouflaging device consisting of four parabolic mirrors and two plane mirrors are shown in Figure 1 and Figure 2 [12,13]. The invisible area is enclosed by four parabolic mirrors M1, M2, M3 and M4, as shown in Figure 1. The parallel incident light is reflected by parabolic mirror M1 and then converged onto focus point N1, on the surface of a plane mirror. Finally, light goes out in parallel way, after it is reflected by M2. The other beam is symmetrically reflected in the identical way. The stealth principle is quite simple, but there are two fatal defects if one tries to use this technique in pillars of vehicles. First, the image is upside down in a horizontal direction, shown in Figure 2; second, when using mirrors in the windshield pillars of an auto, there is no place to put mirrors N1 and N2 invisibly. These two disadvantages make this technique ineffective for use in automobiles.

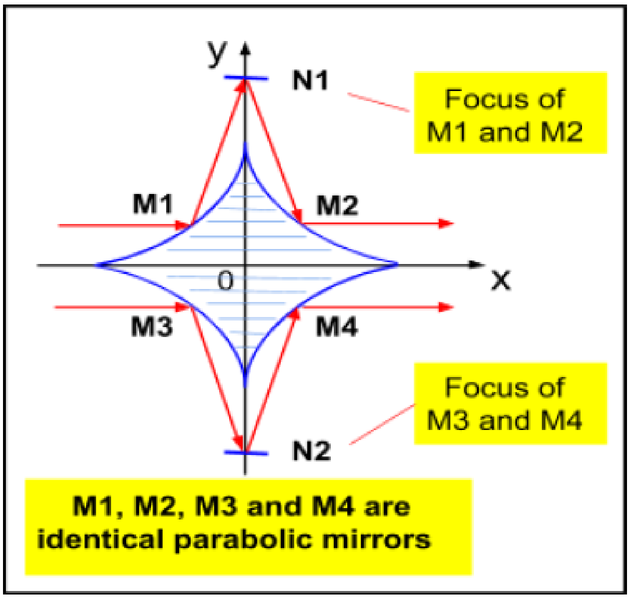

Figure 1. Cross section of Figure 2

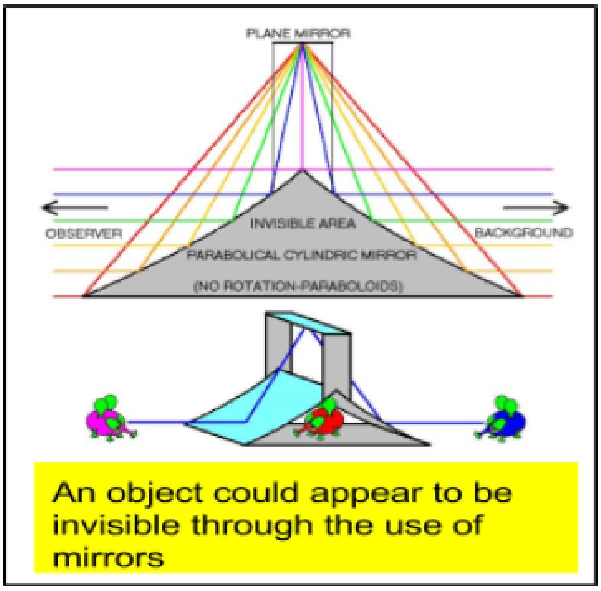

Figure 2. Illustration of parabolic mirrors for stealth

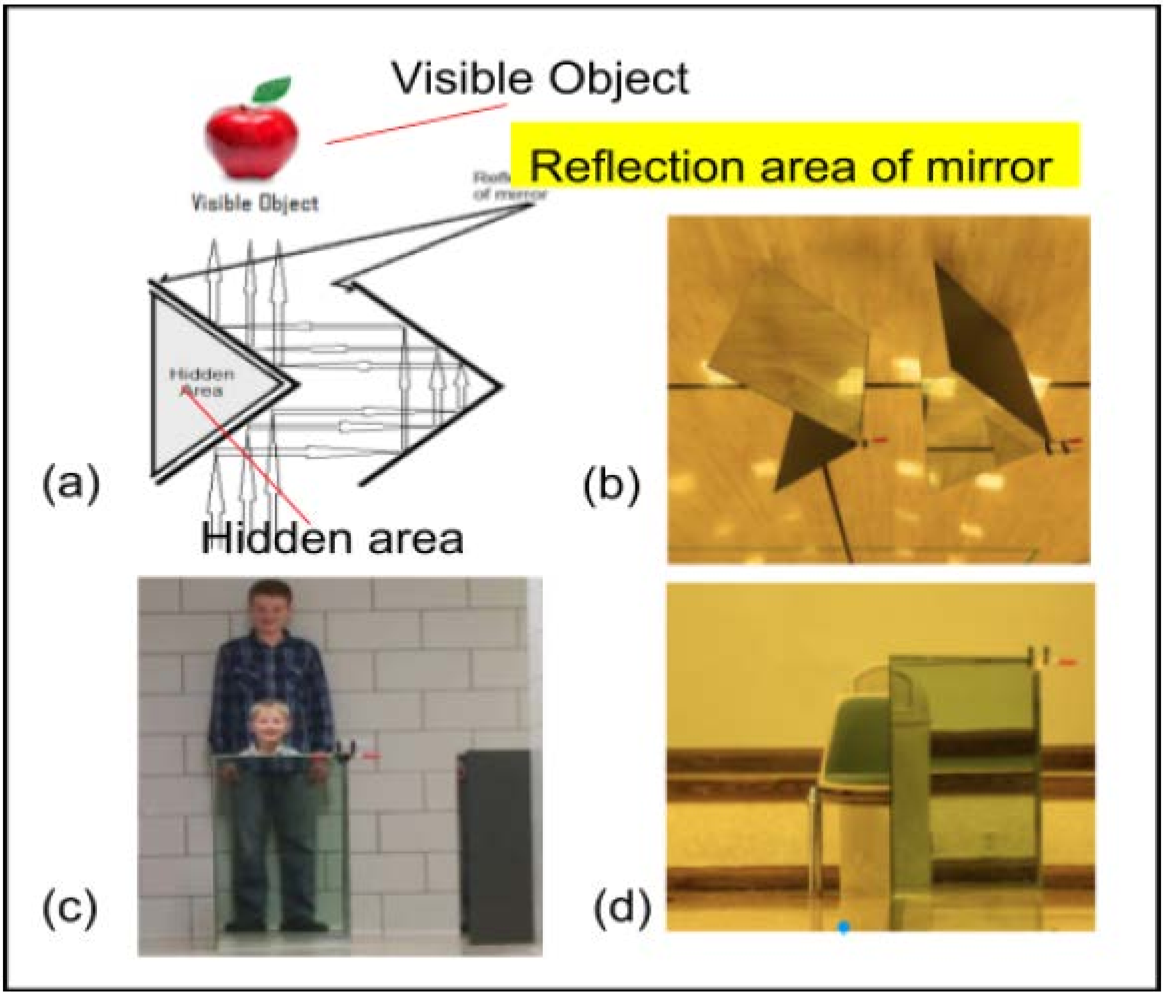

Figure 3. [14] Device plane mirrors for camouflaging

As shown in Figure 3 (a,b,c), two mirrors are positioned at right angles with their reflective area placed outward and the other two with reflective area inward. When positioned correctly, this allows light to be reflected around the hidden area revealing the visible object which is behind the first set of mirrors [14]. Actually, it is obvious that when the cloaking area gets too large, the stealth effect goes down directly as shown in Figure 3 d, because the sight line converges in the observer's eye in a V-like shape instead of in a parallel way. However the fatal defect is that there is no room to place the right mirror when trying to use this in an auto. Consequently, it is not a practical technique to use for camouflaging the A-pillar.

ii) Using a camera to camouflage pillars

Jaguar Land Rover (JLR) hoped to remove blind spots caused by chunky structural pillars and used head-up display projectors to beam a picture of the roadscape onto windscreen pillars to make up for any obscured views [15]. And it was not just the A-pillars; JLR said the aim was to turn all the pillars around the car into video screens, including the B- and C-pillars at the back. Each one took a live video stream from a series of cameras, beaming up footage of vehicles, pedestrians and other objects outside the car for a 360-degree panorama, as shown in Figure 4 (a). Wolfgang Epple, JLR's research and technology director, said: "We are developing this technology to improve visibility and to give the driver the right information at the right time. If we can keep the driver's eyes on the road ahead and present information in a non-distracting way, we can help drivers make better decisions in the most demanding and congested driving environments." Two similar technologies to make the A-pillar invisible are shown in Figure 4 (b) [16] and (c) [17]. These designs do not influence the structure of the pillars and thus the mechanical strength. However, the frame still remains and the color of projected images will inevitably change the natural view blocked by A-pillar, to some extent.

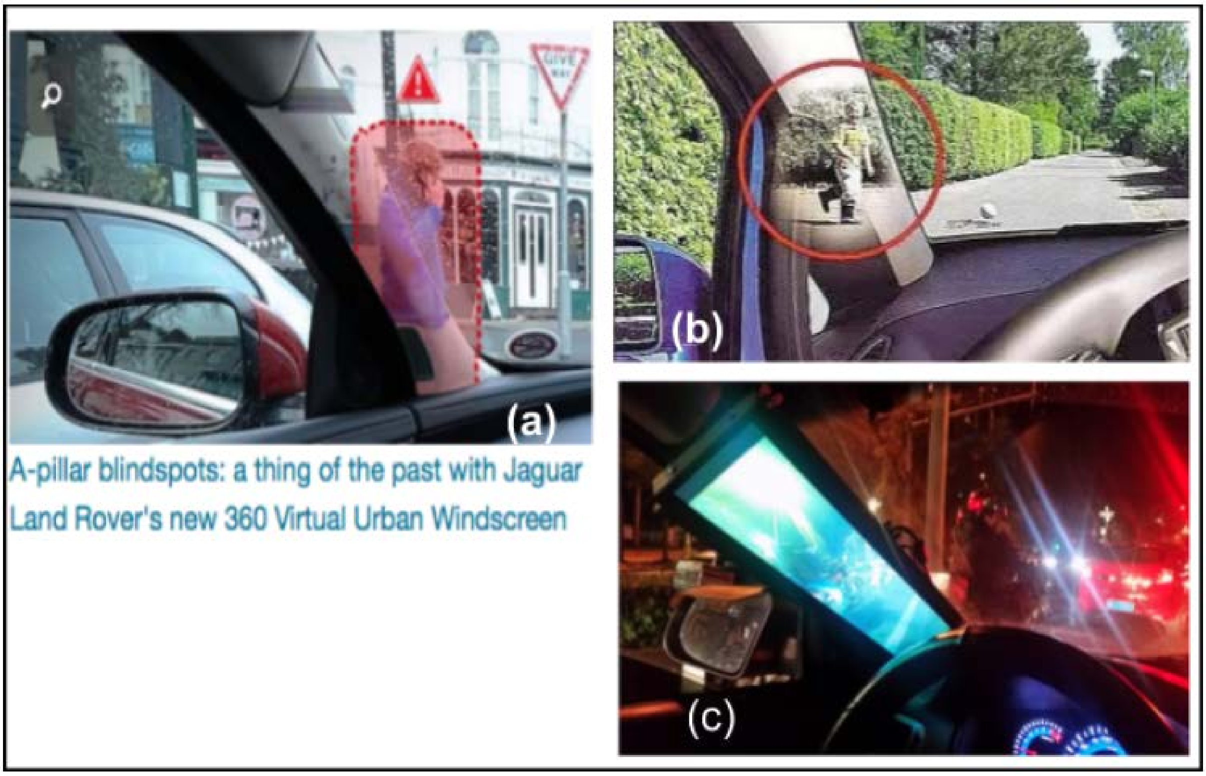

Figure 4. [15] Using the camera to camouflage A-pillar

Figure 5. Lattice-like A-pillar

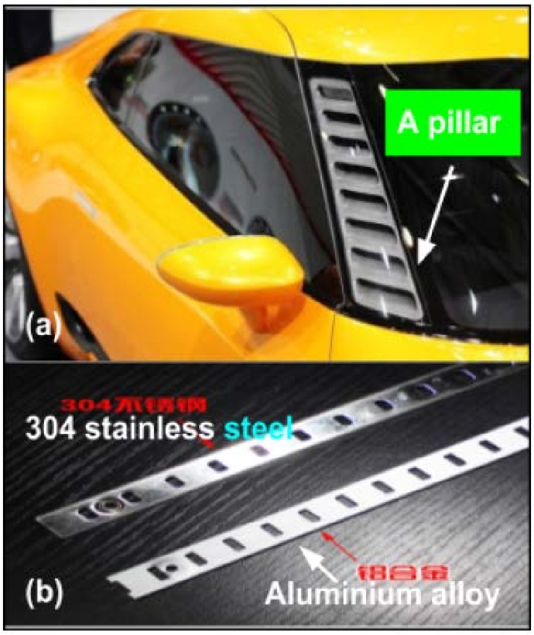

Figure 6. A-pillar with rectangular windows

iii) Using lattice-like A-pillar

As early as 2001, the Volvo car company proposed the Safety Concept Car (SCC) and hollowed out the A-pillar, shown in Figure 5 (a [18], b [19]). Obviously such a lattice-like pillar enlarges the view of the driver considerably and makes the car more comfortable to drive. Some similar technologies were also developed by other designers as shown in Figure 6a and b [20,21].

GT4 Stinger designed the lattice-like A-pillar in 2014 and there is no doubt that compared with the traditional design, such a pillar enlarges the driver's view and reduces the blind spot. It definitely improved the A-pillar.

iv) Shrinking the size of A and B pillars or removing them

Different from all above designs, another design made the pillar triangular and shrunk the size of A-pillars, using steel of super strength, as shown in Figure 7 [22]. This elegant and solid pillar can reduce the area of the blind spot effectively.

Figure 7. Triangular shape A-pillar of small size

v) Removing the pillar

Audi AR boldly and originally removed the A-pillar completely, supporting the windshield only by the roof, shown in Figure 8 [23,24]. The visual field increases perfectly and driving becomes much more comfortable because the blind spots caused by the two A-pillars disappear without a trace. Nevertheless, some suspect the security of the l car. In an accident or roll-over, will the roof hold without the A and B pillars?

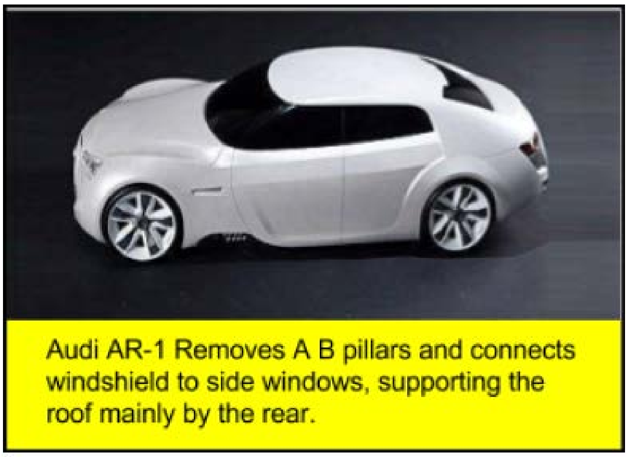

Figure 8. Car without A-pillar

Another endeavor to improve A-pillar was done by Agera R. Both A-pillars are removed but one pillar is installed in the middle of windshield, Figure 9 [18]. It seems the area of the blind spot will decrease significantly, but the security of the roof and windshield is a concern.

Figure 9. Car moving two A-pillars to middle of windshield

vi) Bigger A-pillars focused on enhancing safety

Diametrically opposed to all above cases, research on new A-pillars has focused on enhancing safety, instead of diminishing blind spots [25,26]. In order to meet the new roof-crush standards, ultra-high-strength steel should be used for A-pillars since a vehicle must withstand a force equal to four times its weight before the roof crushes (12.7cm). However, on the other hand, the surface of the two A-pillars must be soft enough to meet federal head-impact standards. Consequently, the size of A-pillars will inevitably grow considerably. At the same time A-pillar blind spots will obscure more sightlines of the driver. How can designers enhance safety without impeding visibility?

Based on all above analyses, a novel way to camouflage A, B, C and D-pillars was invented and is discussed below.

3. The Structural Properties of the Quadrangular Prism of Self Invisibility

i) The structure and one essential exploration

A quadrangular prism of self-invisibility, as shown in Figure 10 (a), is defined as a quadrangular prism that can camouflage itself on its own, without any outer traditional rounding refractive materials or metamaterials or reflected mirrors. Such a quadrangular prism consists of four triangular prisms (1), (2), (3) and (4). The heights of all base triangles of the triangular prisms are the same, with two identical lateral faces of mirrors reflecting invisible light effectively. Two identical triangular prisms, one left (1) and one right (2), are placed at equal height symmetrically and a second pair of triangular prisms (3) and (4) are treated similarly. All the triangular prisms are attached to two transparent rectangular prisms (5) and (6), respectively. All angles of the base triangles of triangular prisms depend strictly and completely on the following three factors: (i) the size of the pillar; (ii) the distance between the pillar and the observer; (iii) the height of the base triangle of the triangular prism. According to the law of light reflection, beams parallel to the rectangular prism are reflected by the relevant lateral faces in sequence as shown in Figure 10(b) and go out of the system as if there are no opaque triangular prisms at all. Therefore, the whole arrangement of quadrangular prisms is camouflaged by itself without special outer materials. The device depicted above is a generalized case when the separation between a pillar and the observer is limited.

A direct extrapolation obtained easily and elegantly is when the separation between a pillar and the observer goes to infinity, the quadrangular prism converts into a rectangular prism and all the base triangles of triangular prisms become identical isosceles triangles as shown in Figure 11(a). The path of incident beams and the light reflected by all the mirror faces as shown in Figure 11(b) are similar to Figure10(b), but are much simpler. In the extrapolation, the relative position between two isosceles triangles becomes simple, being expressed by the following concise formula (1), where EF is the vertical interval between two transparent rectangular prisms; h is the height of base triangle as shown Figure 12(a); θ equals 90 degrees minus the incident angle. The parameters of the relationship between the quadrangular prisms can be shown by the following equations (see Figure 12 a, b), from which equation (1) can be proved strictly from below:

$$EF = h(1 + \tan 2\theta cot\theta) \quad (1)$$

$$\delta + \theta + \alpha = \frac{\pi}{2} \quad (2)$$

$$\phi + 2\theta + \alpha = \frac{\pi}{2} \quad (3)$$

$$\delta' + \theta' + \alpha' = \frac{\pi}{2}. \quad (4)$$

$$\phi + 2\theta' + \alpha' = \frac{\pi}{2} \quad (5)$$

$$2hcsc\delta cos(\delta + \alpha) + hcsc\alpha = EF \quad (6)$$

$$2hcsc\theta' \cos(\theta' + \alpha') + hcsc\alpha' = EF. \quad (7)$$

From (2),(3),(4) and (5), when the separation between a camouflaged pillar and the observer goes to infinity, ϕ goes to zero; consequently, $\delta = \theta = \delta' = \theta'$; both equation (6) and (7) change into $EF = h(1 + tan2\theta cot\theta)$ exactly being the formula (1).

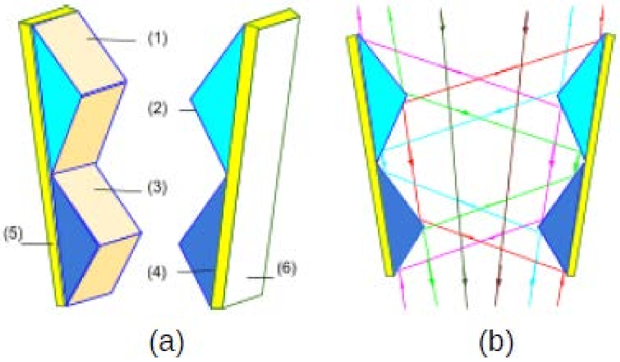

Figure 10. (a) Illustration of the quadrangular prism of self-invisibility (1) and (2) are two identical triangular prisms; (3) and (4) are also identical triangular prisms. (5) and (6) are identical transparent rectangular prisms, (b) The light path by relevant mirrors of lateral faces of all triangular prisms

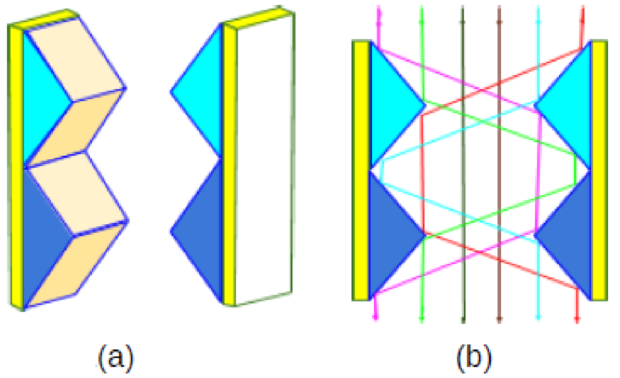

Figure 11. (a) When the distance between a pillar and a observer goes to infinity, the quadrangular prism converts into a rectangular prism and all the base triangles of the triangular prisms become isosceles triangles, (b) The light path of the lateral face mirrors of the isosceles triangular prisms

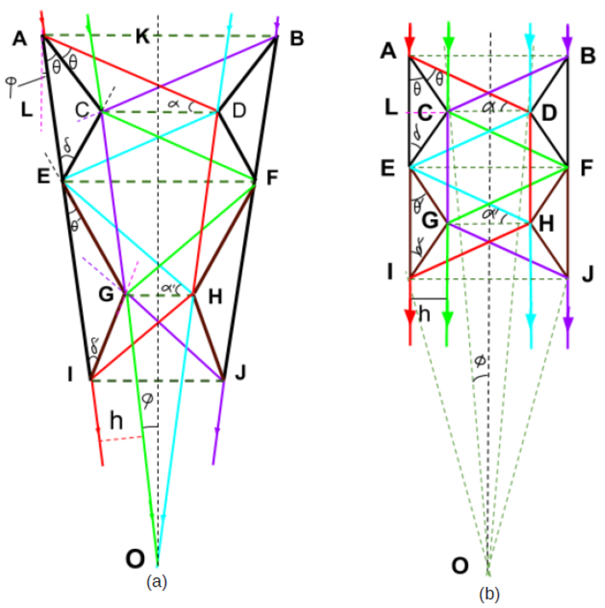

Figure 12(a). The illustration shows all the parameters necessary to determine the whole quadrangular prism of self-invisibility, (b) The illustration shows all the parameters necessary to determine the Extrapolation

ii) the relation between the width and length of invisible prism

Being pillars of a vehicle, the height of the base triangle of quadrangular prism, EF and the length are all the parameters affecting the structural strength of the steering space and the invisible rate for a certain observer's position.

In order to simplify the process of discussion, the relation of width and length of invisible prism can be researched from its extrapolation as shown in Figure 12(b). From equation (1) yields $\frac{dEF}{d\theta} = h(\frac{2\cot\theta}{\cos^2 2\theta} - \frac{\tan 2\theta}{\sin^2\theta}) = 0$, let $\frac{dEF}{d\theta} = 0$ gaining $\cos 2\theta = 1$ then $\theta = 0$ or π. The solution yields $\theta = 0\ or\ \pi$ which is insignificant for practical designs $EF = h(1 + \tan 2\theta cot\theta) = h(1 + \frac{2}{1 - \tan^2\theta})$. if $\theta = \frac{\pi}{4}$, EF goes to infinite and the length of prism $L = 4hcot\theta = 4h$, and $EF = \infty$. The results above definitely indicate that when θ goes up from zero to $\frac{\pi}{4}$, EF also increases to infinite; conversely, the length $L = 4hcot\theta$ decreases from the infinite to its minimum 4h and the area of section of each base triangle $h^2cot\theta$ goes down to h^2. The outcome of the calculation shows the parameters of the quadrangular prism can be adjusted in the light of practical need. This issue will be discussed further below.

4. The Possibility for Use of the Invisible Pillar Invention in Vehicles

i) The geometrical properties A-pillars of vehicle

In order to research the mechanical strength of the invisible A-pillar quantitatively, the concrete geometrical information for the invisible prism should be determined. Figure 13 (a) shows the relative position between the driver's eyes and the two A-pillars of a Lexus car ES300. In order to have a good view for analyses, an abstract model was made as shown in Figure 13 (b) where EF and AC represent two A-pillars and the concrete data are shown in Figure 13(c). It is obvious the data will vary for different heights of various drivers. In other words, the specific driver's position is dependent on a driver's stature and the position of the seat.

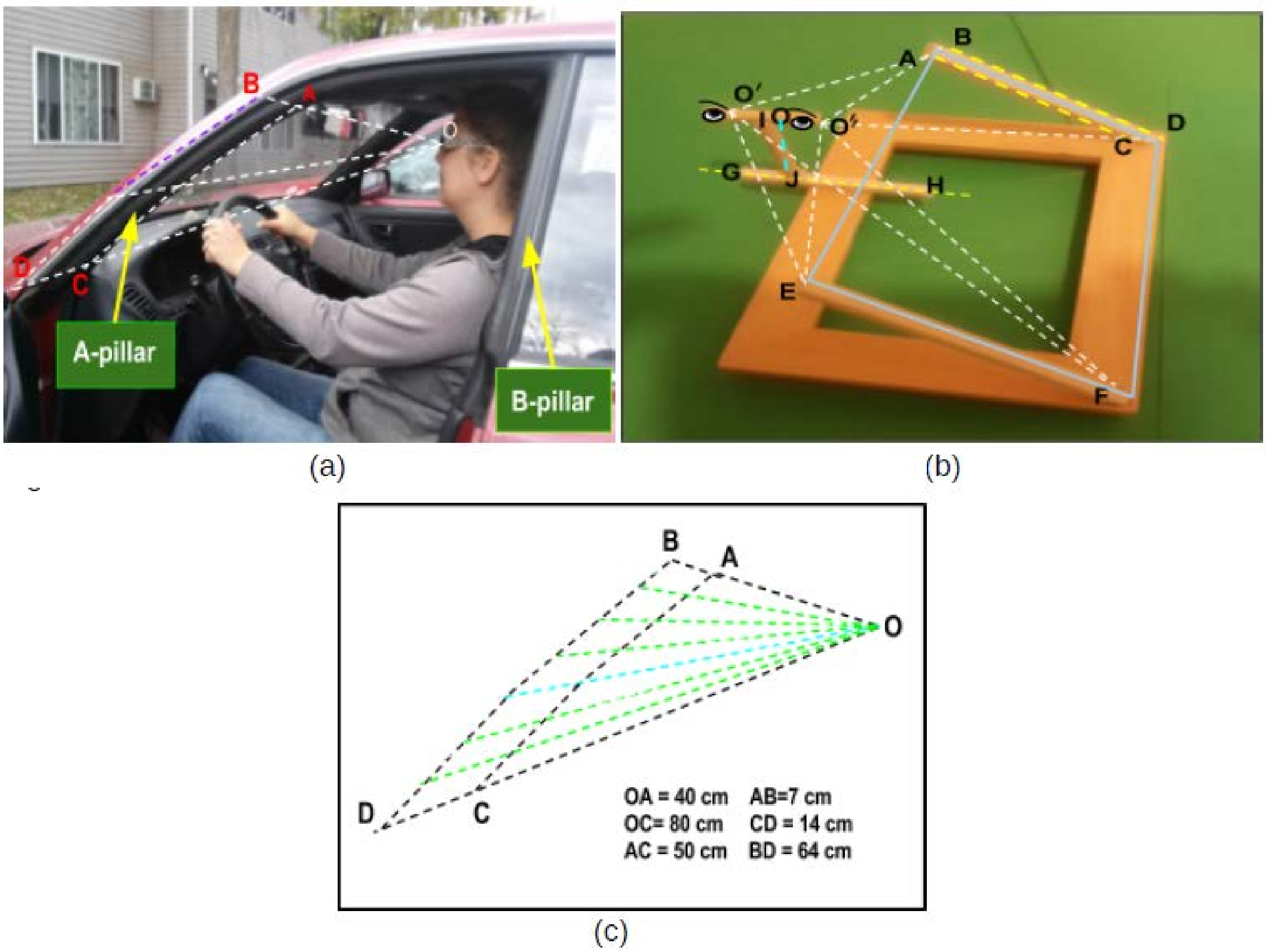

Figure 13. (a) Driver sitting in car, (b) Model of observer point and A-pillars, (c) Some parameters necessary obtained from observer point to A-pillar

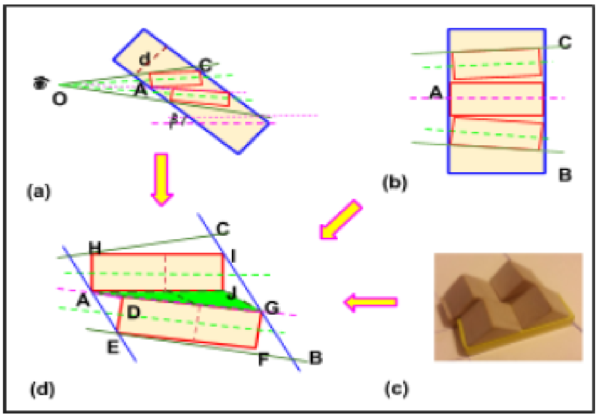

Figure 14. Illustrating for the relation between observer point and A-pillar

The invisible rate will change for different drivers. Therefore, the main subject to be dealt with is how to make an invisible pillar that satisfies the various heights of drivers. Based on the structural characteristics of the invisible prism, there are two factors that affect the invisible rate and mechanical strength. The angle of inclination of pillar to driver's eye β will influence the overlap area of the two prism units. Figure 14 (a) and (b) represent the A-pillars of a car and truck or jeep, respectively. It is quite clear that when β gets close to $\frac{\pi}{2}$, the area of overlap between the two prism units, shown in Figure 14 (c) and (d), increases accordingly. Then the mechanical strength also goes up proportionally. Both the invisible rate and mechanical strength will increase while the overlap area of the two prism units increases correspondingly. The rough data from a driver with a height of 1.75m sitting in the driver's seat of a Lexus ES300 is shown in Figure 13 (a and c). Point O in Figure 13 (b) is the position of a driver's eye with the stature of 1.75 m. $O \pm 10cm$ corresponds to stature range between 1.75 ± 20 cm. Therefore, O' and O'' correspond to observer's point for stature of driver ranging from 155 to 195 cm which covers almost all the heights of various drivers.

It is easy to estimate the size and other relevant magnitudes of the triangular prisms that heaps into the quadrangular prism of self invisibility as shown in Figure 15 (a) illustrating the movement of observer's point in the plane o''go'c. When three parameters OA, ad and h are determined all other ones are also obtained in the light of equals (2) through (7), listed in Table 1. Substituting the data, the invisible rate defined [10,11], can be calculated listed in Table 2. Obviously, tiny changes can be reasonably ignored.

When the position changes from point o to e, the invisible rate be obtained by using the following calculation. $\angle aex=88.06$, $\angle bex=87.76$, $\angle ceo=84.19$, $\angle deo=83.93$. Then the invisible rate= $\frac{(84.19-83.93)+(88.06-87.76)}{180-83.93-87.76} = \frac{0.26+0.3}{8.31}$ =0.067=6.7%, the maximum change of the invisible rate is not larger than 6.7 %.

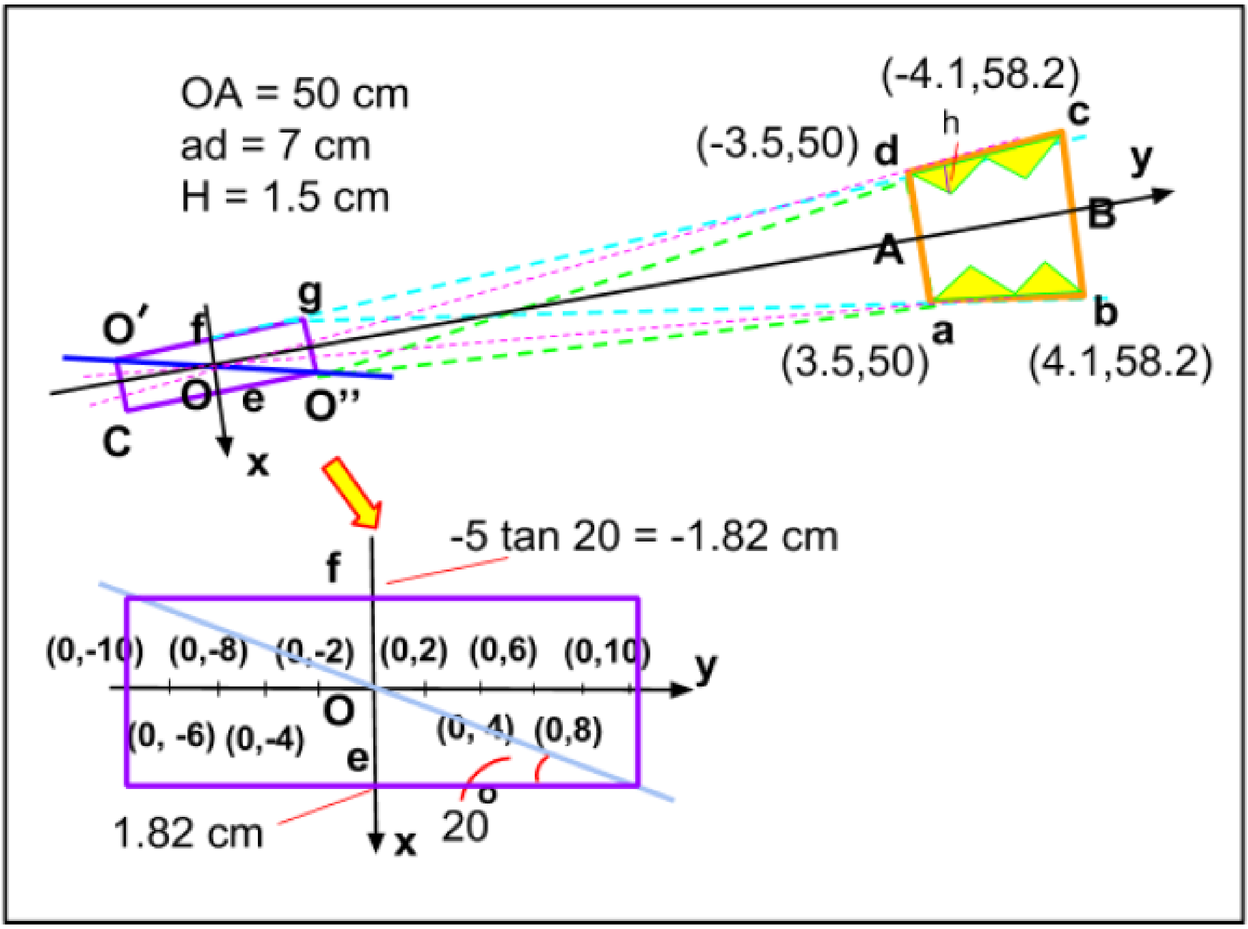

Figure 15. (a) Cross section of right A-pillar and the movement of observer's eye position

Table 1. The data for configuration of invisible prism shown in Figure 15 (a)

Initial conditions	OA	ad	h	
The parameters obtained in the light of equations (2) through (7)	50 cm	7 cm	1.5 cm	
	φ	θ	δ	α
	4^o	36.2^o	40.2^o	13.6^o
	θ'	δ'	α'	ab
	32.7^o	36.7^o	20.6^o	8.17 cm
	cd	bc	AB	
	8.17cm	8.14 cm	8.15 cm	

Table 2. The invisible rate vs the position change 0 ± 10 *cm* along y axis

Coordinate (cm)	(10,0)	(8,0)	(6,0)	(4,0)	(2,0)	(0,0)
Invisible rate (%)	99.1	99.3	99.4	99.6	99.9	100
coordinate	(-2,0)	(-4,0)	(-6,0)	(-8,0)	(-10,0)	
Invisible rate (%)	99.9	99.7	99.6	99.5	99.4	

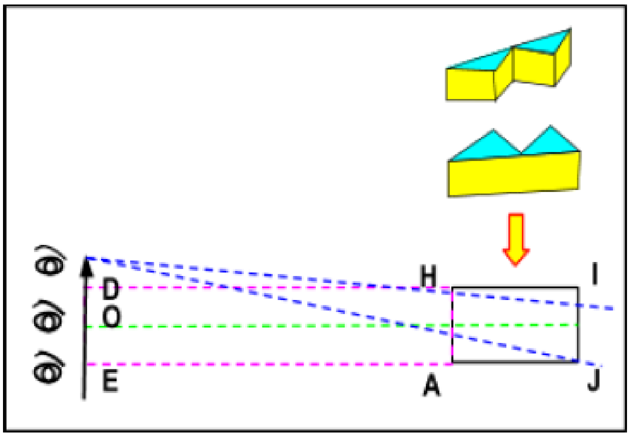

Figure 15. (b) Movement of observer point vs lateral edge of triangular prism

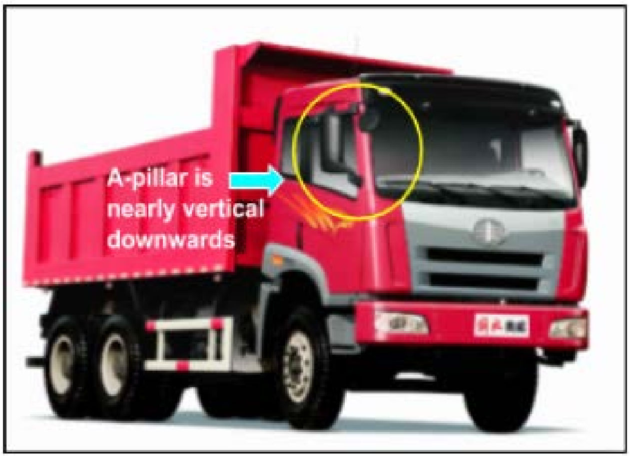

Figure 16. Photo of truck

ii) The mechanical properties of invisible pillars of vehicles

The A-pillar shown in Figure 17 [27] is a cross-section photo of the windshield pillar of a Lexus EV150, the internal steel plate is 2.3 mm thick and the outer one is 1.1 mm thick.

Figure 17. A-pillar of a Lexus EV150

It is well known that when a shaft with a circular cross section is subjected to torque, the cross section remains in plane while radial lines rotate. This causes a shear strain within the material that varies linearly along any radial line, from zero at the axis of the shaft to a maximum at its outer boundary. EJ describes flexural strength, of shaft (also A-pillar here) where E represents the constant of proportionality, which is called the modulus of elasticity or Young's modulus and J is the polar moment of inertia of the cross-sectional area computed about the shaft's longitudinal axis. In order to compare the bending strength of the invisible prism and the traditional A-pillar, the following calculation was carried out. To simplify the process of calculation, an abstract model is shown in Figure 18 (a) to represent the traditional pillar and the invisible prism, shown in Figure 18 and (b) the camouflaged prism replacing the right A-pillar (see Figure 19). In order to get some quantitative conception, let both areas of the cross section be the same and also identical in length and width. Suppose the base angle of triangular prism is $\pi/6$ and its height h equates to 1 for simplification. The process to calculate the bending strength of the invisible prism is as below.

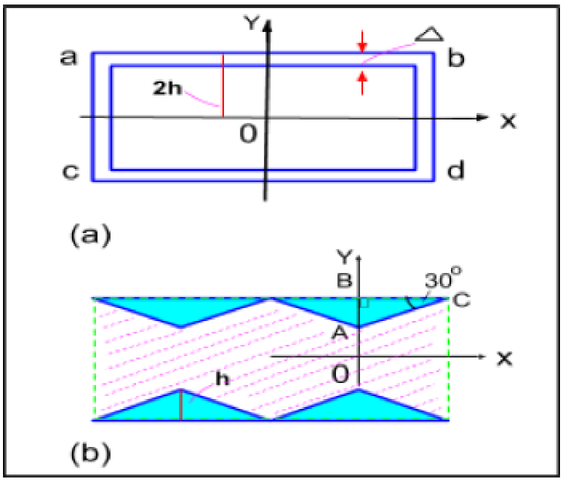

Figure 18. Cross section of a rectangular prism (a) and triangular prism (b)

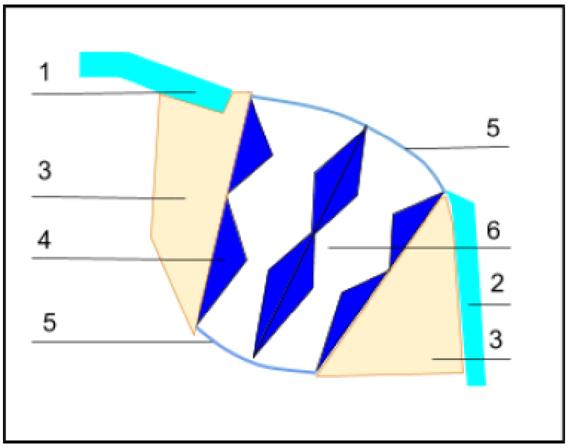

Figure 19. Illustration of an invisible quadrangular prism to replace the conventional right A-pillar of a vehicle, (1) windshield; (2) side window; (3) transparent cushions; (4) the quadrangular prism of self invisibility; (5) transparent covers; (6) transparent material

$$J_1 = 2\int_{2h-\Delta}^{2h} y^2 4\sqrt{3}h dy + 2\int_0^{2h} y^2 2\Delta dy$$

$$= 8\sqrt{3}h\int_{2h-\Delta}^{2h} y^2 dy + 4\Delta\int_0^{2h} y^2 dy$$

$$= 8\sqrt{3}h\frac{(2h)^3}{3}[1-(1-\frac{\Delta}{2h})^3] + 4\Delta\frac{(2h)^3}{3},$$

let h=1, we get

$$J_1 = \frac{64}{\sqrt{3}}[\frac{\Delta^3}{8} - \frac{3\Delta^2}{4} + \frac{3\Delta}{2}] + \frac{32\Delta}{3},$$

$$J_2 = 4\int_h^{2h} y^2 2\sqrt{3}(y-h)dy,$$

let h = 1, yields $J_2 = 8\sqrt{3}\int_h^{2h}(y^3 - y^2 h)dy = \frac{34\sqrt{3}}{3}$

$J_1 = J_2$ then one element cubic equation for Δ can be obtained.

$\Delta^3 = 6\Delta^2 - 14.31\Delta + 4.25$, thus the solution Δ= 0.344 cm.

The results of the calculation indicate that J of the four triangular prisms equals the rectangular prism with a width Δ= 0.344 cm. By comparing Figure 17 to Δ, it is obvious EJ of such a invisible prism is not less than the real A-pillar shown in Figure 17 provided two modulus of elasticity selected E of all steels are the same.

5. The Main Disadvantage and Possible Strategies to Overcome It

Decomposing the motion of observer's position O'O'' into three orthogonal directions, oe, oA and the one perpendicular to cross section o'go''c (see Figure 15a), the changed invisible rate for plane o'go''c is so tiny that it can nearly be ignored as shown in Table 2. The decreased amount for the movement from f to e is not larger than 6.7%. However, the main disadvantage occurs in the third direction, as shown in Figure 15b and it is so severe that it may be fatal to this stealth technology. Figure 15b shows AH=IJ which represents the length of the lateral edge of the triangular prism. If the displacement of the observer's eyes is not in ED range, the light blocked by the area of h timing the length of lateral edge cannot be seen by at least one eye of the driver. This means part of the incident ray cannot reach the observer's eye and the invisible rate will inevitably go down. Increasing the length of the lateral edge seems to improve this situation, but it will decrease the overlap area between the two prism units which directly determine the bending strength.

There are some measures which can be considered to overcome such a fatal defect. The position of the present driver's seat can be changed forwards, backwards, upwards and downwards to some extent. Based on the above functions, if the gas, brake, or clutch pedals can also be equipped to stretch out or draw back, it will be easy to fix the position of the observer's eye, no matter how tall or short the driver is. If all these measures are adopted precisely, the invisible effect can be improved to a great extent.

Before carrying out the above improvement, it is certain that this invisible prism can be used to increase the invisible rate for some existing A-pillars as shown in Figure 20 [18]. The invisible effect for the existing lattice-like A-pillar will easily be improved. Because the direction of the crossbeam can be adjusted to a favorable direction, its mechanical strength remains constant after getting the perfect invisible effect.

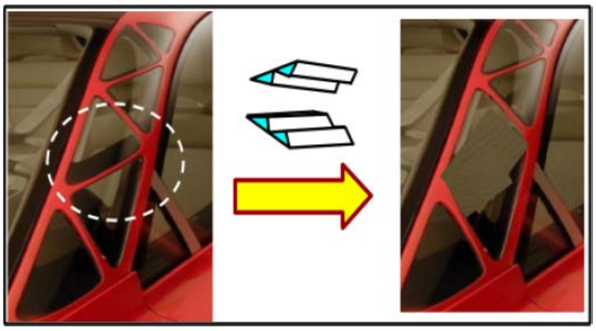

Figure 20. Making a use of quadrangular prism to lattice-like existing A pillar provides a better view field for drivers

6. Discussion and Conclusions

The vehicle industry has been developing for more than one hundred years. In modern society today, the vehicle is an absolutely essential tool for most people all over the world; without it we cannot make a living. Although driverless vehicles have been launched, all the A, B, C and D pillars remain nearly the same as they used to be. In spite of several existing stealth technologies to camouflage even large objects, some real difficulties prevent them being put to use in autos. The conflicting requirements of mechanical strength and minimum obstruction to the driver's view prevent easy solutions. Even so, research on camouflaging all the pillars of vehicle will never cease because of the human instinct to strike a balance between security and comfort.

Figure 14 and Figure 15 (a) illustrate that the greater the separation between the observer and a pillar OA, the better the camouflage effect will be because when OA gets larger, the invisible rate goes down more slowly. Keeping the OA magnitude, when β moves closer to $\frac{\pi}{2}$, the overlap area of two prisms unit will go up; therefore, the invisible effect also increases while keeping bending strength constant. It is more practical to use this new stealth device on trucks and jeeps because the incline angle of A-pillars β is more sharp. The invisible prism is also effective for the A-pillar of cars to a large extent.

The design of all pillars in vehicles of all sorts is a complicated problem concerning several branches of learning: optics, geometry, mechanics of materials, even the evolution of materials relative to temperature. The quadrangular prism of self invisibility quite likely can play an essential role in camouflaging pillars of autos. All the above discussion only relates to the trickiest case, the left A-pillar. It is certain that all the other pillars, right A-pillar, B, C and D pillars are relatively easier to design fulfilling the high invisible rate and bending strength at the same time. Further research on invisible pillars is underway.

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