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TO: Policy Dialog Advisory Committee on Greenhouse Gas Emissions from Personal Motor Vehicles.

FROM: Brian O'Neill

SUBJECT: Vehicle Size, Weight, and Occupant Safety

At the last meeting I promised to provide the Committee with some information on passenger car occupant safety; here it is.

Introduction

Published materials and oral testimony have been presented to the committee that alluded to the safety of advanced low greenhouse gas emission car designs. In some cases this information has been wrong and in others misleading. One example of information that is wrong, is the publication from Amory Lovins that states, "Since composites are so amazingly strong and bouncy, an ultralight, ultraefficient car can also be ultrasafe. Indeed properly designed supercars should prove safer than today's steel cars -- witness the Indy 500 drivers who routinely survive 230 mph crashes in composite vehicles."[1] These statements by Lovins are ultranonsense. "Strong and bouncy" are very undesirable vehicle safety attributes, and Indy drivers do not routinely survive crashes at 230 mph, there are Indy drivers who have survived crashes in the 60-70 mph range, but not without significant injuries. The statement in the *Scientific American* article by John DeCicco and Marc Ross claiming that, "Better crashworthiness comes not from vehicle size or mass itself but from features that safeguard passengers, regardless of vehicle size,"[2] is also wrong.

Other examples of misleading information presented to the Committee occurred in the briefings on electric vehicles and the Partnership for a New Generation of Vehicles (PNGV) program. In the electric vehicle briefing, the claim was made that very small electric vehicles "could be made freeway safe." When the presenter was questioned about what was meant by this statement, the response was that such vehicles would be able to meet all of the existing federal motor vehicle safety standards. Similarly, the presentation on the PNGV program stated that the target of the program was to produce a mid-size car (the size of today's Ford Taurus) that in addition to being more fuel efficient, would weigh substantially less than the equivalent sized car today and that would meet all of the existing federal motor vehicle safety standards.

Both the electric vehicle and the PNGV briefings implied that meeting today's federal motor vehicle safety standards with either smaller and/or lighter vehicles would mean no degradation in occupant safety. This implication is wrong. Meeting the federal motor vehicle safety standards does not produce the same levels of occupant safety or crashworthiness in all cars. Everything else being equal, smaller and/or lighter cars will always offer less protection to their occupants than larger and/or heavier cars. In the mid-1970s small cars had occupant fatality rates that were approximately double the rates for large cars. Despite significant overall reductions in occupant death rates, today's small cars still have rates approximately double those for large cars. Regardless of advances in safety technology, the safety disadvantages for occupants of small and/or lighter cars is inherent in the physics of crashes.

The Physics of Car Crashes

Occupants of passenger cars are injured if they experience forces due to deceleration in duration or amounts that exceed their tolerance for such forces. Reducing the forces experienced by car occupants during a crash is the principle underlying efforts to prevent occupant injury.

For example, when a car traveling at 30 mph is brought to a stop by normal braking, the occupants are decelerated with the occupant compartment and the deceleration is well below injury tolerance thresholds (30-45g's for well-restrained healthy males). Normal braking produces decelerations of 0.2g, with emergency braking being closer to 0.8g. Obviously higher decelerations produce shorter stopping distances and vice versa -- from 30 mph stopping at 0.2g takes 150 feet and at 0.8g it takes 38 feet.

Consider what happens when the same car traveling at 30 mph hits a rigid wall and the stopping distance is very short. To keep the physics simple, we will assume that the occupants decelerate with the occupant compartment just as they do during braking. We will further assume that the front-end of the car crushes one foot with uniform deceleration of the occupant compartment throughout the crash. (Car front-ends do not produce uniform deceleration in actual crashes, and as a result the deceleration is higher in some parts of the crash than others.) In this crash, the occupants will experience 30g's. However, if the front-end of the car crushes two feet instead of one (this means that the front-end has become less stiff), then the deceleration is cut in half to 15g's.

Although doubling the crush distance cuts the deceleration in half, doubling the crash speed in this example from 30 mph to 60 mph increases the occupant deceleration from 30 to 120g's. This latter effect is due to the fact that the kinetic energy of a moving object is proportional to the square of it's speed; in this example, 30^2 equals 900 and 60^2 equals 3,600, hence the four-to-one increase in deceleration.[3]

These examples illustrate two parameters that are important in determining the decelerations and resultant forces experienced by passenger car occupants when they are decelerated with the occupant compartment -- the speed change and the stopping or, in the case of a crash, crush distance.

Modern Car Crashworthiness

Modern car crashworthiness is based on the concept of using crush distance to decelerate occupants with their compartments. The passenger compartment -- the "safety cage" -- is designed to be a rigid structure. The front, rear, and side structures outside of the cage -- the "crush or crumple zones" -- are designed to absorb crash energy by crushing to reduce the forces reaching the occupant compartment.[4]

To protect the occupants, the safety cage should remain intact during a crash so that the occupants can decelerate with it and, at the same time, not be struck by intruding objects.[5] The main purpose of the passenger compartment restraint systems -- belts and air bags -- is to ensure that the occupants decelerate with the compartment. In addition, because there is some distance between the occupants and hard structures inside the compartment, the restraints can provide some additional deceleration distance for the occupants, so that they can experience somewhat lower decelerations than the compartment itself.[6]

The Role of Car Weight

This discussion has focused on the crash of a single car into a rigid wall, but in the real world crashes involve a range of configurations beyond a simple barrier crash. They include single car crashes into objects that may deform during a crash, car-to-car crashes, and car-to-other vehicle crashes. In some of these other configurations the role of vehicle weight becomes important.

The role of car weight in the physics of car crashes can be illustrated by a head-on crash between two cars each traveling at 30 mph. If the two cars are the same and thus have equal weight, this crash is essentially the same event as a single car crash into a barrier, and both cars will decelerate from 30 mph to zero. However, if the two cars have unequal weights, the heavier car will drive the lighter car backwards during the crash, and the resultant velocity (at least during the important part of the crash) will not be zero.

If we now consider the case when one car is twice the weight of the other, then conservation of momentum means that the lighter car is decelerated from 30 mph to zero, and then accelerated backwards to 10 mph. Thus, its speed change during the crash is now 40 mph, while the heavier car experiences a speed change of only 20 mph.[7] This means deceleration distance rather than stopping distance is now important since the two vehicles do not come to rest during the crash event. Because the speed changes are different, the occupants of the lighter car will experience much higher forces than the occupants of the heavier car.

Because of these differences, the occupants of heavier vehicles gain protection in crashes with lighter cars, but only at the expense of the occupants of lighter cars. In other kinds of crashes, such as single-car crashes into objects that are not totally rigid and that may deform in the crash, vehicle mass will increase the likelihood that the impacted objects do deform, thereby increasing the stopping distance for the car's occupants. Adding mass simply to improve crashworthiness, however, would be an inappropriate and societally undesirable approach to design. On the other hand if significantly "downweighted," but not "downsized," cars were to become available as a result of the PNGV program or other environmental initiatives, their occupants would be at greater risk than occupants in similarly sized but traditionally built cars, especially in the earlier years of such vehicles' availability when the bulk of the fleet will be heavier. It is worth noting that a significant number of serious and fatal passenger car two-vehicle crashes involve impacts with trucks -- both light and heavy -- so that even if the fleet of passenger cars eventually becomes a lightweight fleet, weight mismatches will still be common in crashes.

The Role of Crush Distance

The 30 mph barrier crash example presented earlier illustrated the importance of crush distance in reducing occupant compartment decelerations. In that example, one foot of crush distance produces a deceleration of 30g's, but a softer front-end with two feet of crush distance reduces this by half.

Can we use this effect to make things better for the occupants of lighter cars in two-car collisions? The answer is yes if we can increase the crush distance of either car without changing the weight ratio. A way of thinking about this is to consider a two-car head-on crash in which the available crush distance on each car is used to decelerate their occupant compartments. We can improve this crash situation by making the crush space on each car softer and interposing some stationary energy absorbing structure with the same stiffness as the cars' crush space between the two cars. Thus instead of colliding head-on both cars will first simultaneously collide with the energy absorbing structure which provides additional stopping distance for the occupant compartments of both cars and as a result the forces experienced by the occupants are reduced. We would get the same effect with the energy absorbing structure added to either car, if it added no weight.[8] Thus, increasing the crush distance of either car will effectively increase the stopping distance for the occupants of both, because in effect both cars share the additional crush distance.[9] Adding crush distance and making structures softer without significantly increasing vehicle weight becomes a very attractive way to improve crashworthiness.

Implications for Future Vehicles

The preceding examples illustrate the different roles car weight and car size play in occupant safety. Both are important, and those who claim that they need not be important in determining future car occupant safety are, in effect, claiming that the laws of physics can be repealed.

If future vehicle designs intended to reduce greenhouse gas emissions are not going to result in less safe vehicles, it is essential that the physics of car crashes be considered. Crush distance is the most important safety parameter that does not inherently conflict with greater fuel efficiency and/or reduced greenhouse gas emissions. As the examples show, cars with added crush distance can provide increased protection not only to their occupants but also to the occupants of other vehicles with which they may collide. Adding weight, on the other hand, protects but often at the expense of others. It is important to remember, however, that any transition to a fleet of substantially lighter weight cars will mean higher risks to the occupants of these lighter vehicles, especially during the early years of the transition, unless the crush distances are increased. Thus, lighter weight cars should have larger and somewhat softer crush zones to preserve the same occupant safety levels. Such a concept may seem fanciful, but ideas such as those proposed by Carl Clark in which crush distance could be in the form of external air bags that are automatically inflated immediately before a crash, suggest that it may be possible.[10]

Unfortunately, although the United States is willing to invest significant government and private sector resources to develop radically different environmentally friendly cars for the future, nothing comparable is envisioned to ensure that radical safety designs can also be incorporated into these environmentally friendly cars so that they do not produce unnecessary occupant deaths and injuries.

References

1 Rocky Mountain Institute Newsletter, 1993. "The Coming Supercar Revolution," Vol. IX, No. 2.

2 DeCicco, J. and Ross, M., 1994. "Improving Automotive Efficiency," *Scientific American*, Vol. 271, No. 6.

3 In a 230 mph crash (the Lovins example) even a 10 foot crush distance would produce a deceleration of 177g's!

4 It is because of the importance of crush zones -- which are outside the compartment -- that exterior dimensions become the important dimensions for occupant safety issues, rather than the interior dimensions used to define car size by the Environmental Protection Agency.

5 In the case of front-to-side or front-to-rear crashes between two vehicles, the occupants of the struck cars are typically accelerated during the crash but the same general principles apply -- acceleration forces injure just as deceleration forces do.

6 The relevant distances inside the compartment for additional occupant deceleration (driver head to windshield, chest to steering wheel, etc.) are largely independent of exterior car size. This is because all cars must provide interior dimensions to accommodate a range of driver sizes. Cars with small exterior dimensions are not designed to be driven only by small people.

7 This effect illustrates why the "strong and bouncy" vehicle concept advocated by Lovins would be disastrous for occupant safety. Bouncing, which is essentially the same as being driven backwards, essentially guarantees higher speed changes in crashes, with resultant higher decelerations for the occupants.

8 To achieve this improvement it is essential to have compatibility between the crush space stiffnesses of the two cars.

9 This principle is often used in highway work zones, when crushable elements -- often water filled plastic cylinders -- are attached to the rear-ends of slow moving or stationary trucks to ameliorate the potential consequences of a car running into the rear of the truck.

10 Clark, C. 1994. The crash anticipating extended air bag bumper systems. 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, May 23-16, Paper No. 94-S8-W-22.