WINDSHIELD GLASS PENETRATION

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Abstract

Typical JHP bullet velocity loss and deflection from penetrating automobile windshield glass has been measured. Simple analysis of these test results provides useful insight into the dynamics of bullet penetration of windshield glass.

Introduction

The penetration of vehicle window glass with handgun ammunition is a common law enforcement scenario, especially for highway patrol agencies. Windshield automobile glass is heavier than the glass in the doors and rear window, and so presents a more stressing test of ammunition. When the FBI made a reevaluation of handgun ammunition after the disastrous 1986 Miami shootout, they introduced windshield glass as two elements in their revised handgun ammunition test protocol. Other individuals and organizations soon recognized the validity of this approach, and testing of handgun ammunition against windshield glass is now quite common. All of this testing that is known to the authors has not been phenomenological or systematic by engineering standards, and so has left unanswered questions that are not only interesting, but fundamentally important to users and ammunition designers. It is possible that some of the major ammunition manufacturers have done more fundamental testing but have considered this data a "trade secret" and not published it. At any rate, in October 1994 the authors implemented testing to answer some of the fundamental questions related to handgun bullet penetration of windshield glass.

Test Implementation

Several windshields having relatively minor damage were obtained from auto repair shops. Laminated windshield glass on recent model automobiles is standardized by government regulation. The thickness of this standard glass is 5mm, but the thickness on some trucks and on earlier automobiles is nearly 6mm. The bulk of the testing was done using the standard 5mm glass. There is no technical reason to believe that the standard 5mm glass from different sources would give significantly different responses to bullet impact, and the tests indicate that any differences are small.

The test setup included a fixture that held the windshield glass at desired angles, a chronograph (to measure the bullet velocity after glass penetration), a paper target with a small bullseye (to provide a precise aiming point), and gelatin blocks (to catch the bullet). The paper target was 4.04 meters (about 13¼ feet) behind the windshield glass; this distance is obviously much larger than ranges of practical interest (a vehicle interior), but was used to accentuate any bullet deflection from glass impact and thereby reduce deflection measurement errors.

Test ammunition was the Remington .40 S&W 180gr JHP (the California Highway Patrol issue load at the time) and the Winchester Ranger .45 ACP 230gr JHP (the law enforcement version of the discontinued Black Talon). These loads had been previously chronographed at 6 feet and had shown relatively small velocity dispersions; the average velocities were 980 and 855 ft/sec, respectively.

The desired test measurements were the bullet velocity loss and bullet deflection during glass penetration. Bullet deflection was expected to complicate velocity loss measurement and present some threat to replaceable parts of the chronograph. Test data was taken first with bullet impact perpendicular to the glass to minimize the test problems anticipated from bullet deflection; the subsequent testing explored off perpendicular impact and different glass. The test data is described herein in the order that seems most logical ex post facto; this is not necessarily the order in which the data was taken.

Test Data at 90° Incidence Angle

All the .40 S&W load data at 90° incidence angle is given in Table 1. The bullet velocity prior to impact is assumed to be 980 ft/sec (the average for this load in the CHP issue pistol used); this assumption means that the estimated velocity loss δV on any shot may be in error due to muzzle velocity variation from the average value, but the average velocity loss should have small error. The deflections are measured 4.04 meters (about 13¼ feet) downrange from the windshield glass.

Table 1
Remington .40 S&W 180gr JHP data
at 90° incidence angle

glass	V_{exit} ft/sec	δV ft/sec	deflection - cm horiz	vert
5mm #1	802	178	+2	-5
5mm #1	815	165	-9	-6
5mm #1	796	184	+0	-4
5mm #1	788	192	+0	-5
5mm #1	786	194	-2	-4
ave	797	183	2	-5
5mm #2	769	211		
5mm #2	769	211		
5mm #2	777	203		
5mm #2	797	183		
ave	778	202		
6mm	725	255		
6mm	703	277		
6mm	724	256		
ave	717	263		

The difference in the velocity loss between the two 5mm windshields is not necessarily statistically significant. The increased velocity loss with the 6mm windshield is very plausible for the difference in thickness.

No regular deflection was expected due to glass penetration at 90° incidence angle, and this data confirms this. It appears that there is a small random deflection caused by the glass penetration (note: 5cm is approximately 2 inches). Ed Fincel fired all of the rounds in the entire test sequence using a hand rest, and under these conditions the firing dispersions are negligible compared to the impact dispersions seen in the tests. Deflections were not measured for the second 5mm sheet or the 6mm sheet because by the time this data was taken shots through glass at angles had made it clear that this data was of little interest.

All the .45 ACP load data at 90° incidence angle is given in Table 2. The bullet velocity prior to impact is assumed to be 855 ft/sec (the average for this load in the standard M1911A pistol used). All other conditions were the same as for the .40 S&W tests.

Fewer total shots were taken with this round, but the velocity loss is still quite consistent. The second 5mm windshield again causes slightly more velocity loss, suggesting that this variation might be real and not a statistical artifact.

Table 2
Winchester Ranger .45 ACP 230gr JHP
data at 90° incidence angle

glass	V_{exit} ft/sec	δV ft/sec	deflection - cm horiz	vert
5mm #1	708	147	+0	+0
5mm #1	704	151	+0	+0
ave	706	149	+0	+0
5mm #2	652	203		
5mm #2	694	161		
5mm #2	678	177		
ave	675	180		

Photographs of typical bullet deformation from 90° incidence angle on windshield glass for these loads are shown in Figure 11-5 on page 292 of the book *Bullet Penetration - Modeling the Dynamics and the Incapacitation Resulting from Wound Trauma*. This deformation is almost all due to contact with the glass; as explained in Chapter 7 of *Bullet Penetration*, a bullet with the shape and velocity existing at glass exit has very little deformation in gelatin. The Winchester Ranger .45 ACP 230gr JHP diameter increase as a result of the glass impact is smaller than the diameter increase for the Remington .40 S&W 180gr JHP. This relatively smaller diameter is a factor in the slightly smaller velocity loss of the Winchester Ranger .45 ACP.

The dynamics of the velocity loss is discussed in more detail in a subsequent subsection.

Test Data at Incidence Angles Below 90°

The windshield glass was tilted so the incidence angle was entirely in the vertical direction (i.e., the horizontal incidence angle was 90°). All the .40 S&W load data at 60° incidence angle is given in Table 3; all other conditions were the same as for the 90° incidence angle tests.

Table 3
Remington .40 S&W 180gr JHP data at 60° incidence angle

glass	V_{exit} ft/sec	δV ft/sec	deflection - cm horiz	vert
5mm #1			-10	-2
5mm #1			-6	+0
5mm #1			-9	+0
5mm #1	757	213	-11	-4
5mm #1	792	188	-11	-3
ave	780	200	-9	-2

It is obvious that there is no deflection from penetration of the glass at an angle; the vertical deflections are smaller than the horizontal deflections. The absence of any deflection from penetration of the glass at an angle was not expected, but a subsequent subsection of this paper explains this result using the penetration dynamics determined in these tests. The random dispersion in deflection is about the same size as for the 90° incidence tests.

No attempt was made to measure the velocity loss for the first three shots because the expected deflection had to be determined to avoid damage to the chronograph. After the first three shots it was clear that the nominal deflection was zero, so velocity was measured on the last two shots. Since there was no deterministic deflection, it was no surprise that the velocity loss was similar to the 90° incidence tests.

All the .45 ACP load data at 60° incidence angle is given in Table 4; all other conditions were the same as for the 90° incidence angle tests.

Table 4
Winchester Ranger .45 ACP 230gr JHP data at 60° incidence angle

glass	V_{exit} ft/sec	δV ft/sec	deflection - cm horiz	vert
5mm #1			-7	+0
5mm #1			-16	+0
ave			-11	+0

The deflection was again only small and random; by happenstance, there was no measured deflection in the vertical axis (that had the 60° incidence angle). Velocity loss was not measured.

The lack of deterministic bullet deflection at 60° incidence angle did not necessarily preclude deterministic deflection at smaller angles; in fact, theoretical considerations seem to ensure deflection when the incidence angle is very small. It was decided to test for deflection at the smallest incidence angle that the fixture could reliably support the windshield; this turned out to be 34°. The fixture had not been designed to hold the glass at very low angles because it was believed (correctly) that very low angles do not represent practical shooting scenarios. It can reasonably be argued that even the 34° incidence angle is below conditions that are practical in field shooting scenarios (not only geometrically but visually).

All the .40 S&W load data at 34° incidence angle is given in Table 5; all other conditions were the same as for the 90° incidence angle tests.

Table 5
Remington .40 S&W 180gr JHP data at 34° incidence angle

glass	V_{exit} ft/sec	δV ft/sec	deflection - cm horiz	vert	
5mm #1			-9	-5	
5mm #1			-24	-2	
5mm #1			-15	-9	
5mm #1			+9	+4	
ave				-10	3

Even at the 34° incidence angle there was no indication of deflection in the vertical axis. The horizontal axis, which still had a 90° incidence angle, seemed to have larger random deflection variations, but it is hard to see how this could be other than happenstance. It is very easy to delude yourself into seeing a pattern in random numbers when no pattern or cause is really there; problems associated with not understanding statistics are discussed in some detail in Chapter 3 of *Bullet Penetration* (in the context of misinterpreting data from combat shootings).

The Elementary Dynamics of Bullet Penetration of Windshield Glass

This subsection includes analysis in enough detail to permit easy checking by interested readers, but the detail calculations can be skipped to get directly to the conclusions in the associated text description.

Velocity loss through the standard 5mm windshield glass was about 150-200 ft/sec for the limited testing of JHP loads at angles of incidence between 90° and 60°. Velocity loss for incidence angles below 60° was not measured, but the similarity of deflection results at 34° suggest that the velocity insensitivity extends to at least 34°. Very limited testing indicates that velocity losses through the 6mm glass are about 30% higher.

It is informative to simplistically analyze the dynamics of bullet interaction with windshield glass by considering the bullet momentum change and the interaction with the glass that can be derived from this. The .40 S&W load will be used in this analysis. The change in the bullet momentum is easily expressed; it is $m\delta V$, where m is the mass of the bullet and δV is the change in velocity. For the .40 S&W bullet $m = 180/7000/32.174 \approx 0.00080$ slug and the average velocity change is $\delta V \approx 190$ ft/sec, so $m\delta V \approx 0.00080(190) \approx 0.15$ lb-sec. (This is the correct unit, and you don't have to worry about how it works out to be.) This 0.15 lb-sec is the momentum lost by the bullet as it penetrates the windshield glass.

Part of the momentum lost by the bullet is transferred to the mass of the glass that is driven out of the bullet path. It is not easy to calculate this exactly because there is a wide range of velocities for the various glass fragments, but we can easily make bounding approximations. A lower bound is obtained by assuming that a cylinder of glass of the initial bullet diameter and the glass thickness is accelerated to the bullet velocity after glass penetration. An upper bound is obtained by assuming that a cylinder of glass of the deformed bullet diameter and the glass thickness is accelerated to the bullet velocity after glass penetration. In actuality, glass from a larger diameter is removed (the hole in the glass is larger than the bullet), but part of this glass is at a much lower velocity (the glass fragments that are left near the impact point). The true momentum transfer is probably closer to the upper bound model than to the lower bound model.

The volume of the assumed upper and lower bound glass cylinders are about 0.40 and 0.80 cubic centimeters. At the typical specific gravity of glass (2.6) the lower bound glass mass is $2.6(0.40) \approx 1.04$ grams ≈ 16 grains ≈ 0.000071 slugs; the upper bound mass is twice this, or 0.000142 slugs. The change in velocity is the bullet exit velocity (the glass is initially not moving), or about 790 ft/sec. Then the upper and lower bounds for the change in glass momentum are about 0.055 and 0.11 lb-sec, respectively. These bounds represent about 35% and 70% of the bullet momentum loss, so it appears that approximately half to two thirds of the bullet momentum change (or velocity loss) is absorbed in momentum loss change in the glass. This momentum exchange is entirely due to inertial forces, and so has nothing to do with the "strength" or "toughness" of the glass. The inertial forces do depend on the glass density, but this is about the same for all manufacturers.

Another interesting parameter that can be deduced from this penetration data is the average force the glass exerts on the bullet during the penetration. The total change in the bullet momentum calculated above for the .40 S&W bullet tested is 0.15 lb-sec; this momentum change is equal to $F\delta t$, where δt is the time interval for the penetration and F is the average force on the bullet during that interval.

The time interval of the penetration can be estimated simply with reasonable accuracy. The first step is to determine the average velocity of the bullet during the penetration, which will be calculated as the average of the velocities before and after glass penetration. These velocities are 980 and 790 ft/sec, respectively, which gives an average of 885 ft/sec. The effective distance the bullet travels during the penetration is more complicated than might be simplistically assumed; this complexity comes from the fact that the nose of the bullet is being deformed during the penetration. The correct way to determine the effective distance the bullet travels during the penetration is to consider how far the base of the bullet travels during the penetration; this distance includes not only the 5mm glass thickness, but also the distance the nose of the bullet is "pushed back" toward the base. The photographs in *Bullet Penetration* (pages 195,200, and 292) show that this nose regression distance is about 2.5mm, so the total effective distance the bullet travels during the penetration is about 7.5mm ≈ 0.30 inch ≈ 0.025 foot. The time elapsed in traveling 0.025 foot at 885 ft/sec is $0.025/885 \approx 0.000028$ second. The average force can then be calculated as $F = 0.15/0.000028 \approx 5400$ lbs.

The force on the bullet varies considerably during the glass penetration, but the average force can still be used to give an indication of the dynamics during the penetration. The frontal area of the bullet contacting the glass is a minimum when it first touches the glass; this small annular area is less than 1/30 of a square inch, so the average force corresponds to a pressure of over 160,000 psi (5400 lbs divided by 1/30 inch squared). This pressure will cause yielding in almost all metals, including most steel alloys. The maximum frontal area of the expanded bullet is about 2/3 of a square inch (at the end of glass penetration), so the average force would correspond to a minimum pressure of about 8000 psi for this area (5400 lbs divided by 2/3 inch squared). This minimum bound on the average pressure is far above the yield point of lead (which is below 3000 psi - see page 127 of *Bullet Penetration*), so the bullet lead deforms at a force level well below the average force during penetration. The first deduction from this observation is that typical JHP bullets deform throughout the glass penetration. The second deduction from this observation is that a round or pointed nose bullet will undergo at least some deformation during glass penetration even if constructed of high quality steel (and such a bullet would be very inferior in wounding effectiveness). The overall conclusion is that any ordinary bullet will always be significantly deformed during the penetration of windshield glass; it is not possible to eliminate this deformation, so bullet design must be directed towards making the ultimate deformed shape as desirable as possible. Bullet design to accommodate a wide range of incidence angles in windshield glass penetration is a very difficult design problem.

Bullet Deflection Dynamics

The approximately 5400 pound average force on the bullet calculated in the previous subsection provides an explanation for the absence of an observed deterministic bullet deflection from the windshield glass penetration. This force is very much higher than the force the glass will support in a small area, and the glass fractures with very small deflection, so the momentum impulse delivered to the bullet by the glass is very small before initial glass fracture occurs. Once the glass fractures, the shear force it can support is reduced to a negligible value. The principal shear force support after glass fracture is the organic laminate (probably polyvinyl butyral) between the glass plates; penetrating this laminate causes most of the bullet momentum loss that is not due to inertial forces. The penetration of this laminate at a 90° incidence angle by the bullet and the glass fragments from the first plate will inevitably be somewhat asymmetric, and so introduces lateral forces on the penetrating bullet that are unpredictable in magnitude and orientation. This laminate penetration asymmetry effect seems to be roughly the proper magnitude to account for the observed random bullet deflection during windshield glass penetration, and is probably the cause of it. It superficially appears that this effect should be different at differing incidence angles (and so would introduce a deterministic deflection), but any incidence angle effect is negated when the total penetration is considered. A JHP bullet that impacts windshield glass at an angle undergoes deformation that tends to produce a contact surface that is parallel to the initial glass (and laminate) surface, so the laminate is contacted by a surface that is approximately flat and parallel to it for all incidence angles from 90° down to at least 34°. Note that the deviations from flat and parallel that are indicated by the "approximately" can go either way and are a major contributor to the small random deflections.

Some JHP bullet designs might show a deterministic deflection, but the insights into windshield glass penetration phenomenology that have been gained from this testing make this appear improbable. It would be prudent to verify the observed windshield glass deflection characteristics for any load that is expected to be used in this scenario, and the authors would be pleased to learn of any such testing.

Conclusions Relative to JHP Bullet Deflection by Windshield Glass

Limited testing of typical JHP handgun bullets shows that windshield glass penetration seldom causes a bullet deflection angle greater than 2° for incidence angles between 90° and 34°. This deflection angle is not consistent in magnitude or orientation relative to incidence geometry; it seems to be essentially random. The expected deflection is small (less than 2 inches for a target located anywhere in a typical automobile), and no compensation is possible because the deflection angle is unpredictable.

The bullet deflection by windshield glass impact should be ignored in tactical situations involving an officer firing into an automobile. This includes not having mental reservations or concerns about this deflection; don't worry about it, it is not important.