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PREDICTED EFFECT OF PROJECTILE DISPERSION ON TARGET HIT PROBABILITIES AND DISPERSION-ZONE SIZES FOR THE 25-MM GUN OF THE BRADLEY FIGHTING VEHICLE

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This research note presents the mathematical analysis used to predict the effect of varied levels of projectile dispersion on a) dispersion-zone size, and b) hit probabilities for targets engaged with the 25-MM gun of the Bradley Fighting Vehicle. This provides critical background information on issues such as accuracy criteria for zeroing, maximum effective engagement ranges, and the training aids used to illustrate the effects of dispersion.

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FOREWORD

Since 1975 the Army Research Institute (ARI) has contributed to a program to define emerging problems and address critical issues affecting the Bradley Fighting Vehicle (BFV). Consistent with that program, this report describes the predicted effects of 25-mm projectile dispersion on target hit probabilities, dispersion-zone sizes, zeroing, and maximum effective engagement ranges. This report is intended for project managers associated with development of gunnery standards and guidelines for the BFV.

ARI's Fort Benning Field Unit, a division of the Training Research Laboratory, monitored the research reported here. ARI's mission is to conduct research of training and training technology using infantry combat systems and problems as mediums. The research task which supports this mission is titled Advanced Methods and Systems for Fighting Vehicle Training and is organized under the "Train the Force" program area. Sponsorship for this research effort is provided by a Memorandum of Understanding (effective 31 May 1983) between the U.S. Army Infantry School (USAIS), TRADOC, Training Technology Agency and ARI, which established how joint efforts to improve BFV tactical doctrine, unit, and gunnery training would proceed.

PREDICTED EFFECT OF PROJECTILE DISPERSION ON TARGET HIT PROBABILITIES AND DISPERSION-ZONE SIZES FOR THE 25-MM GUN OF THE BRADLEY FIGHTING VEHICLE

EXECUTIVE SUMMARY

Requirement:

To predict the effect of varied levels of projectile dispersion on (a) dispersion-zone size and (b) hit probabilities for targets engaged with the 25-mm gun of the Bradley Fighting Vehicle (BFV) to provide critical reference information related to maximum effective engagement ranges and zeroing.

Procedure:

Predicted hit probabilities (HP) were calculated for three types of targets: zeroing (4-, 6-, and 8-foot squares), a fully-exposed frontal view of a BMP (2 meters x 3 meters), and a hull-defilade frontal view of a BMP (1 meter x 2 meters). The HPs were calculated for dispersion values of 0.3 to 1.0 mils (standard deviations) for target ranges at 200-meter intervals up to (a) 1600 meters for zeroing targets and (b) 3000 meters for BMP-sized targets. Projectile dispersion zones also were calculated for varied levels of dispersion to provide information related to zeroing criterion.

Findings:

For a dispersion level (0.8 mils) that was near the maximum allowed value for training ammunition, HPs were (a) 90% or greater for an 8-foot square zeroing target for ranges of 800 meters or less and (b) less than 50% for a fully-exposed frontal view of a BMP at ranges as short as 1600 meters. For the maximum allowed dispersion level (0.5 mils) for armor-piercing ammunition that is fired from a BFV, analysis indicated (a) a 90% or greater HP for an 8-foot square zeroing target at ranges of 1200 meters and less, (b) a 68% HP for a fully-exposed frontal view of a BMP near the tracer-burnout range, and (c) a 90% dispersion zone that was about 2 mils in diameter.

Utilization of Findings:

Findings provide critical information for (a) determining maximum engagement ranges for training, qualification, and combat, (b) determining zeroing ranges and criterion, and (c) developing training aids to illustrate the effects of projectile dispersion on hitting targets.

PREDICTED EFFECT OF PROJECTILE DISPERSION ON TARGET HIT PROBABILITIES AND DISPERSION-ZONE SIZES FOR THE 25-MM GUN OF THE BRADLEY FIGHTING VEHICLE

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Background

Since August, 1983, the Fort Benning Field Unit of the Army Research Institute (ARI) and its resident contractor, Litton Computer Services, have conducted research to develop training and improve operational effectiveness of the Bradley Fighting Vehicle (BFV) under all visibility conditions. A major emphasis has been to develop an understanding of factors which affect the accuracy of 25-mm gunnery. One such factor is dispersion which is deviation in the predicted trajectory (and point of impact) of a projectile.

The maximum allowed dispersion is specified by a measure of variability called the standard deviation. The larger the value, the more round-to-round variability in the location of impact. The armor piercing discarding sabot-tracer (APDS-T) round has a lower dispersion requirement (0.44 mils) than high explosive incendiary-tracer (HEI-T) ammunition (0.77 mils); training practice-tracer (TP-T) has the same requirement as HEI-T ammunition. The higher dispersion value for HEI-T ammunition makes it well suited for engagement of area targets while the lower dispersion of APDS-T provides greater accuracy against point targets like the BMP.

Ammunition is the most frequently discussed source of dispersion; however, there are other causes like the weapon and the weapon's platform. Conditions for tests of dispersion depend on the source of dispersion that is being examined. Ammunition dispersion is tested in a rigidly mounted gun barrel that is not allowed to move before, during, or after firing. Weapon dispersion is tested with the gun mounted in a benchrest to prevent weapon movement. Measurements of weapon dispersion are confounded by ammunition dispersion because it is virtually impossible to produce dispersion-free ammunition. Additional factors that may contribute to dispersion are barrel movement, a loose muzzle brake, and a worn barrel. Weapon-system dispersion is tested with the fully operational weapon system mounted on the weapon's platform. When APDS-T ammunition is fired in the single-shot mode, round-to-round dispersion should not exceed 0.5 mils (standard deviation) in the horizontal and vertical planes at 1000 meters (Department of the Army, 1978).

Dispersion affects target hit probability. The likelihood of a hit decreases as target range increases for a given level of dispersion. Furthermore, the higher the dispersion level, the lower the target hit probability at a given target range. Therefore, dispersion affects maximum effective engagement ranges.

Dispersion also affects zeroing. As dispersion increases, the accuracy of zeroing decreases because impact location of a single round may not represent the average center-of-impact. In this case, sights can be adjusted based on the center of a shot group. Excessive levels of dispersion also can decrease hit probability on the zeroing target making it more difficult for the gunner to make accurate sighting adjustments.

Knowledge of the impact of dispersion on target hit probabilities is critical for determining gunnery performance standards. Gunnery performance during training and qualification is affected when training ammunition is substituted for service ammunition. Substitution of TP-T for APDS-T ammunition significantly reduces target hit capabilities for vehicular targets. Despite this, at the time the current analysis was conducted, the BFV Gunnery field manual presented identical crew qualification standards when TP-T ammunition was substituted for APDS-T ammunition (FM 23-1, 1983; 1986).

Problem

Excessive dispersion was observed to disrupt training at Fort Benning during late 1983 and early 1984. Negative effects of dispersion were noted during zeroing and target engagement with TP-T ammunition. In general, gunners really were not sure whether erratic ammunition or gunner errors were the major contributor to target misses. The TRADOC Systems Manager, USAIS and the BFV Program Manager's Office later indicated that a couple of lots of fielded ammunition had excessive levels of dispersion. Despite this information, there still was little available information on the effects of dispersion on gunnery performance and target hit capabilities.

Purpose

The purpose of this analysis was to predict the impact of dispersion on gunnery accuracy; the analysis did not measure actual gunnery accuracy resulting from dispersion. The data generated by this analysis could be used to predict the effects of dispersion caused by ammunition, the weapon, or the entire weapon system.

The effects of different values of dispersion were calculated using two measures. Target hit probabilities were determined for typical target sizes engaged with the 25-mm gun. Dispersion zones also were calculated for varied levels of dispersion; these zones indicate the size of circle (diameter in mils) where a certain percentage of rounds should hit. For a 50% dispersion zone, on the average, 5 of 10 rounds should hit in the dispersion circle or zone. This analysis developed a data base that:

- Provided mathematical procedures for calculating hit probabilities and the size of dispersion zones;
- Predicted target hit probabilities under ideal conditions for typical targets engaged with the 25-mm gun;
- Developed critical information for determining maximum engagement ranges for training, qualification, and combat;
- Developed critical information for establishing zeroing ranges and criterion;
- Developed training aids to illustrate the effects of dispersion on hitting targets.

Method

Calculation of Hit Probabilities

Predicted hit probabilities were calculated for three different types of targets: zeroing-sized targets, a fully-exposed frontal view of a BMP, and a hull-defilade frontal view of a BMP. Target sizes for zeroing targets were 4-, 6- and 8-foot squares. The recommended size of zeroing targets in the draft version of the gunnery manual (FM 23-1, 1983) was 4 feet, the size specified in a later version of the manual was 6 feet (FM 23-1, 1986), and boresighting/zeroing targets at Fort Benning measure about 8 feet.

The selected size of a fully-exposed frontal view of a BMP was 2-meters high and 3-meters wide, which are common dimensions used in ballistic research. The author is unaware of standard dimensions for a hull-defilade BMP. The selected dimensions were 1-meter high and 2-meters wide; this height represents slightly more exposure than would be expected for a BMP in hull-defilade position. The 2-meter width is a rough approximation of a BMP-2 turret which is wider than the BMP-1.

Calculations were based on the assumption that the population standard deviation for dispersion was identical for both the x- (azimuth) and y-axes (elevation) and that x- and y-coordinates for each round were independent. Target center-of-mass was assumed to be center-of-impact.

For the analysis of hit probabilities, the target was divided into equal size quadrants with the common boundary between the four quadrants being the target center-of-mass. The size of each quadrant in the x- and y-dimensions was converted to an angular measurement in mils (1 mil = 1/6400 of a circle). The z-score for x- and y-axes was determined by dividing the target size in mils by the population standard deviation (i.e., the level of dispersion).

A table with cumulative normal probabilities was used to determine the probability associated with the z-score for both x- and y-dimensions of the target. The hit probability for one quadrant of the target was calculated by multiplying the probabilities associated with the x- and y-axes. The overall target hit probability was four times that obtained for a single quadrant.

Calculation of Dispersion Zones

Dispersion zones are circles when equal dispersion exists in azimuth (x-axis) and elevation (y-axis) directions of round impact; the center of the circle is the average center-of-impact. For the analysis, the size (diameter in mils) of dispersion zones was calculated for hit probabilities of 25, 50, 75, 90, and 95%. The size of a dispersion zone for a particular hit probability will increase as dispersion increases so dispersion-zone size was calculated for dispersion values (standard deviations) of 0.35, 0.4, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mils.

Dispersion zones were calculated using isodensity contours (Tatsuoka, 1971, p. 62). The following equation applies to a bivariate normal distribution.

$$\frac{(X-\mu_x)^2}{\sigma_x^2}+\frac{(Y-\mu_y)^2}{\sigma_y^2}-2\rho\,\frac{(X-\mu_x)(Y-\mu_y)}{\sigma_x\sigma_y}=C$$

This equation represents a circle when standard deviations for the x- and y-axes are equal. The circle is called an isodensity contour whose area represents the dispersion zone for a particular probability. The above equation can be simplified to determine dispersion zones for varied levels of dispersion. If the correlation between the azimuth (x-coordinate) and the elevation (y-coordinate) is assumed to be zero, then the preceding equation reduces to the following.

$$\frac{(X-\mu_x)^2}{\sigma_x^2}+\frac{(Y-\mu_y)^2}{\sigma_y^2}=C$$

The values of μ_x and μ_y represent the centroid or the overall center-of-impact. With these values set at zero, then the equation becomes:

$$\frac{X^2}{\sigma_x^2}+\frac{Y^2}{\sigma_y^2}=C$$

In this analysis, the dispersion in both axes is assumed equal; therefore, the isodensity contour will be a circle centered at x = 0 and y = 0. The radius of the circle will then be either the x- or y-intercept. The x-intercept is solved for as follows:

$$X^2 = \sigma_x^2 \,(C - (Y / \sigma_y^2))$$

$$X = \sigma_x \sqrt{C}$$

The final equation represents one-half the total width of the dispersion zone. The diameter of the dispersion zone is solved by:

$$D = 2\,\sigma_x \sqrt{C}$$

In conclusion, to determine the diameter in mils of a particular dispersion zone, multiply the standard deviation of the dispersion times the square root of the C-value obtained from the Chi-Square Table for 2 degrees of freedom for a given probability. For example, to determine the 50% dispersion zone, the user accesses the Chi-Square Table to read under the 0.50 column for 2 degrees of freedom. This value is then doubled.

Findings and Discussion

Target Hit Probabilities

Predicted target hit probabilities were based on variations in projectile dispersion, target size, and target range. Tables 1, 2, and 3 present target hit probabilities for zeroing targets, a frontal exposure of a BMP, and a frontal exposure of a BMP in a hull-defilade position, respectively. The hit probabilities can be used as a predictor of either ammunition, weapon, or weapon-system dispersion. Data in the tables will be discussed in the following subsections on Zeroing and Maximum Effective Engagement Ranges.

Target hit probabilities are undoubtedly higher than would be obtained in training and combat. Predictions were based on assumptions of a center-of-mass aiming point and a correct range control setting; probabilities reflect the effect of dispersion and no other factors to include aiming errors, range estimation errors, environmental influences, and equipment errors.

Dispersion Zones

Table 4 presents dispersion-zone sizes (in mils) for varied levels of dispersion. The following is an example of how to read the table. With a dispersion of 0.8 mils, 90% of the rounds (i.e., a 90% dispersion zone) should hit within a circle 3.43 mils in diameter.

The gunnery manual for the Abrams tank (FM 17-12-1, 1982) provides a good description of the importance of dispersion zones (mils). The manual states that when the size of the 90% dispersion zone is smaller than the visual size (mils) of the target, there is a high target hit probability when range is accurately determined.

Zeroing

The recommended zeroing range for the 25-mm gun is 1200 meters. For a dispersion value slightly higher than the maximum allowed value for TP-T and HEI-T ammunition (i.e., 0.77 mils), target hit probabilities for 6-foot square targets (currently recommended size) and 8-foot targets (currently used size) at 1200 meters are only 45 and 65 percent, respectively. Hit probability for an 8-foot square target does not reach 90% until a range of 800 meters. The potential for zeroing TP-T ammunition at 800 meters has been discussed in a separate report (Perkins, 1987a).

Table 1

Predicted Target Hit Probabilities (%) for Zeroing Targets

		Dispersion (standard deviation in mils)									
Target range (m)	Target size (ft)	.30	.35	.40	.45	.50	.60	.70	.80	.90	1.00
400	4 x 4	100	100	100	100	100	98	95	90	84	78
	6 x 6	100	100	100	100	100	100	100	99	98	96
	8 x 8	100	100	100	100	100	100	100	100	100	100
600	4 x 4	100	99	98	96	93	84	74	65	56	49
	6 x 6	100	100	100	100	100	98	95	90	84	78
	8 x 8	100	100	100	100	100	100	99	98	96	93
800	4 x 4	98	95	90	84	78	65	54	45	40	32
	6 x 6	100	100	99	98	96	90	82	73	65	57
	8 x 8	100	100	100	100	100	98	95	90	84	78
1000	4 x 4	93	86	78	69	62	49	37	32	26	
	6 x 6	97	98	96	93	88	78	67	57	49	42
	8 x 8	100	100	100	99	98	93	86	78	69	62
1200	4 x 4	84	74	65	56	62	38	29	23	20	16
	6 x 6	98	95	90	84	78	65	54	45	34	32
	8 x 8	100	99	98	96	93	84	74	65	56	49
1400	4 x 4	74	63	54	46	37	29	22	19	15	12
	6 x 6	95	89	82	74	67	54	43	35	29	25
	8 x 8	99	98	95	91	86	74	63	54	46	37
1600	4 x 4	65	54	45	38	32	23	19	15	12	9
	6 x 6	90	82	73	65	58	45	35	29	24	20
	8 x 8	98	95	90	84	78	65	54	45	38	32

Table 2

Predicted Target Hit Probabilities (%) for a 2 Meter by 3 Meter Target

Target range (m)	Dispersion (standard deviation in mils)									
	.30	.35	.40	.45	.50	.60	.70	.80	.90	1.00
400	100	100	100	100	100	100	100	100	100	99
600	100	100	100	100	100	99	98	96	94	90
800	100	100	100	99	99	96	92	87	81	75
1000	100	100	99	97	96	90	83	75	68	60
1200	100	98	96	94	90	81	72	63	55	48
1400	98	96	92	88	83	72	62	53	45	39
1600	96	92	87	81	75	63	53	44	37	31
1800	94	88	81	74	68	55	45	37	30	26
2000	90	83	75	68	60	48	39	31	26	22
2200	86	77	69	61	54	42	33	27	22	18
2400	81	72	63	55	48	37	29	23	27	15
2600	77	67	58	50	43	33	25	20	16	14
2800	72	62	53	45	39	29	22	18	14	12
3000	68	57	48	40	35	26	20	15	13	10

Table 3

Predicted Hit Probabilities for a 1 Meter by 2 Meter Target

Target range (m)	Dispersion (standard deviation in mils)									
	.30	.35	.40	.45	.50	.60	.70	.80	.90	1.00
400	100	100	100	100	100	96	93	89	84	79
600	100	98	97	94	91	97	93	69	61	55
800	97	93	89	84	79	59	59	51	44	38
1000	91	85	79	72	66	55	46	38	32	28
1200	8[illegible]	76	69	61	55	44	36	29	24	20
1400	76	68	59	52	46	36	28	23	18	15
1600	69	59	51	44	38	29	23	18	14	12
1800	61	52	44	38	32	24	18	14	12	10
2000	55	46	38	32	28	20	15	12	10	8
2200	49	40	34	28	23	17	13	10	8	7
2400	44	36	29	24	20	14	11	9	7	6
2600	39	32	26	21	17	12	10	7	6	5
2800	36	28	23	18	15	11	8	6	5	4
3000	32	26	20	16	13	10	7	6	4	4

Table 4

Predicted Diameter of Dispersion Zones (mils)

	Dispersion (standard deviation in mils)									
Dispersion zone (%)	.30	.35	.40	.45	.50	.60	.70	.80	.90	1.00
25	.45	.53	.61	.68	.76	.91	1.06	1.21	1.36	1.52
50	.71	.82	.94	1.06	1.18	1.41	1.65	1.88	2.12	2.35
75	1.00	1.17	1.33	1.50	1.67	2.00	2.33	2.66	3.00	3.33
90	1.29	1.50	1.72	1.93	2.15	2.58	3.00	3.43	3.86	4.29
95	1.47	1.71	1.96	2.20	2.45	2.94	3.43	3.91	4.40	4.89

Dispersion zone analysis can provide preliminary data on the accuracy that can be expected during zeroing. The 90% dispersion zone for a dispersion of 0.8 mils (slightly higher than the maximum allowed value for TP-T ammunition) has a diameter of 3.43 mils. The radius of the zone (1.72 mils) provides an estimate of error during zeroing. Given the worst case for ammunition with no other dispersion related errors allowed, zeroing with TP-T should result in errors up to 1.7 mils in 90% of the cases.

For a dispersion value of 0.5 mils, which is the maximum allowed value when APDS-T is fired from a gun mounted on a BFV, the 90% dispersion zone has a diameter of 2.15 mils. The currently recommended zeroing standard for APDS-T ammunition requires the round to hit in the 1-mil diameter circle of the ISU (FM 23-1, 1986). Data from this analysis indicates that is an unrealistic criterion. A separate ARI report (Perkins, 1987b) recommends zeroing procedures and criterion for both TP-T and APDS-T ammunition.

Maximum Effective Engagement Ranges

Gunnery qualification tables listed in the first two versions of the BFV gunnery manual (FM 23-1, 1983; 1986) include vehicular targets at a maximum range of 2200 meters. Standards are the same for all types of ammunition (HEI-T, TP-T, and APDS-T). When dispersion (i.e., 0.80 mils) is slightly greater than the maximum allowed value for TP-T ammunition (i.e., 0.77), target hit probabilities are 27% at 2200 meters for a frontal view of a BMP while hit probabilities for APDS-T would be at about twice that value. For this reason, it is unrealistic to expect the same gunnery performance standards when TP-T is used for targets that would normally be engaged with APDS-T. Generally, the maximum effective engagement range for vehicular targets is shorter for TP-T ammunition relative to APDS-T ammunition.

A recent change to the BFV Gunnery manual (FM 23-1 (C1), 1986) has included separate gunnery tables for TP-T and APDS-T ammunition. The maximum range of target engaged with APDS-T ammunition is 1800 meters, which is near tracer burnout range. Table 2 indicates a hit probability of 68% for a frontal silhouette of a BMP target at 1800 meters. The crew is given 8 rounds to achieve 3 hits which is a much lower required hit percentage (38) than the predicted hit probability; this suggests that the new performance standard can be achieved.

Another change in the gunnery manual sets the maximum target range of 1600 meters for target engagements with TP-T ammunition. For a dispersion value of 0.80 mils, Table 2 indicates a hit probability of only 44% for a frontal-silhouette of a BMP. This value is only slightly higher than the hit percentage (38) required of the crew when using TP-T ammunition (FM 23-1 (C1), 1986). It must be noted that the predicted hit probabilities in Tables 1 through 3 probably underestimate the true hit probability which is affected by factors that include range estimation errors, aiming errors, weapon-system errors, and environmental influences. Given this, the new standard may be difficult to obtain for long range targets (e.g., 1600 meters) engaged with TP-T ammunition.

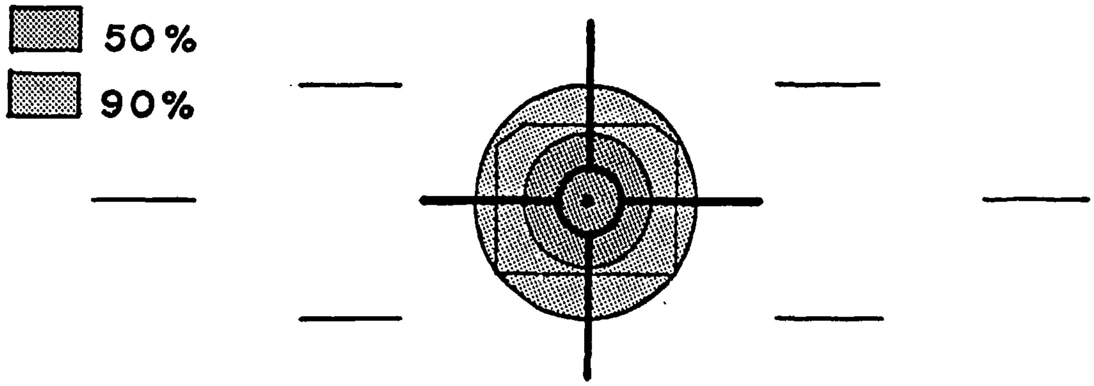
Information in the hit probability tables could be used in combat development of weapon systems designed to engage vehicular targets. If a particular hit probability is required at a particular range, then the tables can be used to determine the required level of system dispersion.

Tactical literature (e.g., FC 7-7J, 1985) often specifies a single maximum effective engagement range; however, this range will be affected by the amount of exposed target. Comparison of hit probabilities for a frontal view of a BMP (Table 2) and a BMP frontal view while in a hull-defilade position (Table 3) indicates that the likelihood of hits is noticeably lower for the latter condition. For dispersion values close to the maximum level allowed for APDS-T ammunition, target hit probabilities were about 35 percent lower for the defilade position.

Training Aids

When gunners train with TP-T ammunition, it often is difficult to determine when their own errors or projectile dispersion contributes to target misses. The gunner should be given some guidance as to the expected dispersion of the ammunition. This can be achieved using dispersion zones overlaid on scaled targets as illustrated in Figure 1.

TP-T DISPERSION



RANGE=1200m

Figure 1. Dispersion zones superimposed on a 25-mm reticle aimed at a frontal silhouette of a BMP at 1200 meters.

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