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MOTION CHARACTERISTICS AFTER RICOCHET: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

The ricochet behaviour of the air–water trans-media vehicle (AWTMV) during water-entry crossing was experimentally investigated. Three types of small-scale AWTMV including cone, ogive, and flat nose were used in the test. The underwater trajectory, velocity, and inclination angle of projectiles during the ricochet process were obtained using a high-speed camera. The angle change of the AWTMV and the ratio of the residual velocity are introduced. Based on this result, the relationship between the ricochet responses and initial conditions was derived. The results of this study show that (1) a small incident angle and great velocity make the occurrence of ricochet behaviour easier, (2) the stability of the trajectory of projectiles with cone, ogive, and flat nose weakened in turn at the same initial conditions, (3) the angle change and the ratio of the residual velocity are linear functions of the incident angle and velocity.

Keywords: air-water trans-media vehicle (AWTMV),ricochet,nose,initial conditions,responses

INTRODUCTION

Possessing all the advantages of single-medium vehicles, such as unmanned aerial vehicles (UAV) and unmanned underwater vehicles (UUV), a vehicle that travels both in the air and under the water is referred to as an air–water trans-media vehicle (AWTMV) [1]. The AWTMV can overcome the limitations of single-medium vehicles with its aquatic–aerial amphibious operation. In recent years, increasing attention has been paid to the AWTMV for its high value in military and civilian applications.

According to the hypothetical mission and purpose of the AWTMV, a complete motion cycle includes four processes: aerial flight, water-entry crossing, underwater navigation, and water-exit crossing [2, 3]. Of these, the water-entry crossing is the key stage for the AWTMV to achieve a smooth transition from the air into water. However, the forces on the AWTMV dramatically change due to the change in the medium from air to water, which may cause the failure of the water-entry crossing and harm the subsequent mission the of AWTMV [4].

The theory and combat applications of the ricochet of spinning and non-spinning spherical projectiles have been summarised in the literature [5, 6]. Based on a large number of test results, the critical ricochet angle expression is proposed in [7], indicating that the result of water-entry depends on the incident angle and the ratio of density rather than the velocity. A new definition of ricochet based on the kinetic energy loss ratio is proposed in [8], and critical ricochet curves were obtained based on the experimental and numerical results. A water-entry crossing model of a pointed-headed projectile drawing on the theory of water drifting was established in [9], indicating the maximum sinking depth of the centre of mass and maximum continuous ricochet. Experimental investigations on the relationship between the critical ricochet angle and the properties of wood have been carried out in [10], indicating that the critical ricochet angle differs and depends on the calibre and wood type and both density and hardness have a strong linear relationship with the critical angle. A mathematical model was established in [11]; based on this, a conclusion was deduced that in the nose-type configuration, the material of the projectile and the incident speed have a weakening effect on the ricochet. An experiment with a projectile obliquely penetrating concrete was carried out in [12], and the critical ricochet angle of the projectile was analysed and estimated. The critical ricochet angle of the projectile's target was predicted in [13], and the angle range in which the projectile does not jump was established. A simulation study on the small-angle water-entry process of the projectile with different apex angles and density was reported in [14]. The effect of the initial conditions on the ricochet has been explored in [15], and the whole ricochet process and the variation in the parameters by changing the incident angle, velocity, and angle of attack have been investigated in detail.

The abovementioned literature indicates that the effect of the initial conditions on the ricochet behaviour has been investigated in detail; however, the subsequent research on the post-ricochet behaviour is rarely investigated; in addition, there are no reports on whether the AWTMV can re-enter the water after ricochet behaviour. In fact, it is necessary and meaningful to guide the re-entry of the AWTMV into the water by studying the motion characteristics after the ricochet.

In this study, the ricochet behaviour was experimentally investigated. Three types of scale projectiles (the small-scale AWTMV is denoted as a projectile for easy description) were used in the experiment with angle-adjustable devices. The effect of the initial conditions and nose-types on the ricochet behaviour was investigated, and the relationship of the initial conditions and ricochet responses was established.

EXPERIMENTAL SETUP

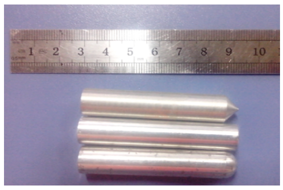
The test device consists of a launching subsystem, a data-acquisition subsystem, and an observation subsystem. Compressed air is used as the power to propel the projectile to move in the test, and the launching speed is changed by adjusting the launching pressure. The launching subsystem is mounted on an angle-adjustable support. The motion of the projectiles was obtained using a high-speed camera VW-6000 (Keynes Company). Due to the high number of frames taken using high-speed cameras and the short exposure time, natural light cannot meet the requirements. Therefore, two lights are placed in front of the observation window of the water tank, and one light is placed behind it.

Note that the launching tube is placed at a certain position away from the water surface to prevent the effect of the residual compressed air after the launch on the water surface. The shooting conditions of 2000 frames/s and 1/4000 s of exposure time were used.

(a) Experimental equipment

(b) Launch subsystem

(c) Air compressor



(d) Three types of projectiles

Fig. 1 Experimental devices

Three types of projectiles with different noses including a cone, ogive, and flat nose were used in the test, and their parameters are listed in Table 1.

Tab. 1. Parameters of projectiles

No.	Nose type	Length (mm)	Diameter (mm)	Mass (g)
#1	Cone	60	12	17.05
#2	Ogive	60	12	17.58
#3	Flat	60	12	18.13

Different launching angles make the distance different for the projectile, which may cause different incident velocities at the same launching pressure. To eliminate the effect of the launching angles on the experimental results, experiments were carried out under the following launching conditions: launching pressure, 1.2 MPa, nose, ogive; and launching angles, 10, 25, and 40°. The incident velocity was obtained, as listed in Table 2.

Tab. 2. The incident velocity at different launching angles

Launching angle (°)	10°	25°	40°
Incident velocity (m/s)	122.1	125.5	127.2

Table 2 indicates that when only the launching angle is changed, the incident velocity of the projectile varies slightly under the same launching pressure. The difference between the maximum and minimum velocity is only 5.1 m/s.

Similarly, the three projectiles are not of exactly the same mass, which may result in different launching velocities. To eliminate the effect of the mass of the projectile on the launching velocity, experiments were carried out under the following conditions: launching pressure, 1.2 MPa; launching angle, 25°; nose-types, cone, ogive, and flat. The results show that the difference in the maximum and minimum incident velocity is only 6.4 m/s.

Tab. 3. The incident velocity at different launching angles

Nose-type	Cone	Ogive	Flat
Incident velocity (m/s)	129.7	125.5	123.3

The comparison of the experimental results in Table 2 and Table 3 shows that the change in the incident angle has little effect on the launching velocity under the same launching pressure. Similarly, the launching velocity is not much different under the same initial conditions for the three types of projectiles. Therefore, in the following experiments, it is considered that: (1) the initial velocity of the projectile is the same under the same initial conditions, regardless of its nose-type structure; (2) when the launching pressure is the same, the initial velocity is independent of the launching angle.

Two types of behaviour were observed in the water-entry experiments: sinking and ricochet. With the impact on the water and the continuous action of hydrodynamics, the velocity of the projectile gradually decreases, and the inclination angle continues to change. As long as the projectile enters the water and then jumps out of the water, it is defined as a ricochet. Otherwise, it is defined as sinking.

For the vehicle with a given shape, the post-ricochet velocity V_o and the post-ricochet angle θ_o, also called the ricochet response, are generally considered to be a function of incident conditions (velocity and angle). To study the relationship between the ricochet responses and the initial conditions, two variables named the angle change $\Delta\theta$ and the ratio of the residual velocity V_o/V_i are introduced.

The angle change $\Delta\theta$ is defined as $\Delta\theta=\theta_i+\theta_o$. The angle change $\Delta\theta$ rather than the post-ricochet angle θ_o was used to minimise the relative error in measurement. By introducing the angle change, it can be judged whether the projectile has a ricochet behaviour, and it can also be used as a criterion for evaluating the stability of the underwater trajectory. When the projectile enters the water at the same incident angle, a large angle change means a more unstable underwater trajectory of the projectile.

The ratio of the residual velocity is defined as V_o/V_i. The velocity is the embodiment of the kinetic energy. When the projectile enters the water at the same incident angle, the ratio of the residual velocity is larger, indicating that the ricochet ability is strong, and the underwater trajectory stability is weak. When the velocity is too small, the projectile will sink due to insufficient kinetic energy to jump out of the water. By introducing the ratio of the residual velocity, the relationship between the post-ricochet velocity and angle and the initial velocity was investigated.

RESULTS AND DISCUSSION

The projectile numbered # 1 was selected and tested at different launching angles to observe its trajectory and parameters during the water-entry crossing. The incident angle is 10°, the launching pressure 1.2 MPa, and the results are shown in Fig. 2.

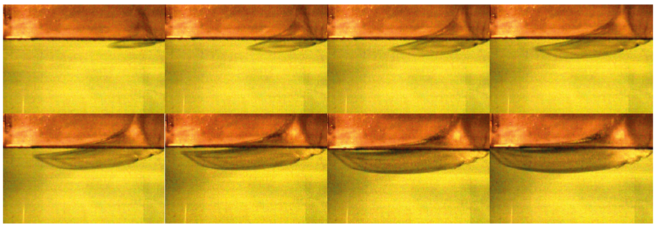


Fig. 2. Experimental results obtained by high-speed camera

Fig. 3 shows the underwater trajectory, and the horizontal and vertical axes represent the horizontal and vertical displacement, respectively. The underwater trajectory of the projectiles has the same trend: all three bend upwards, indicating the ricochet behaviour. The cone has the maximal curvature of trajectory and is the first to jump out of the water.

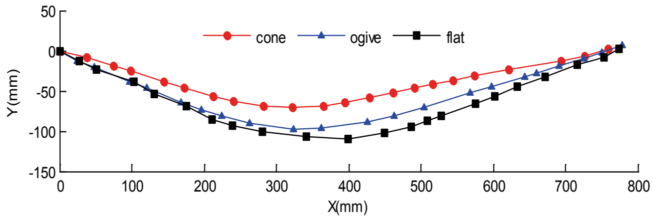


Fig. 3. The trajectory of the projectile

Fig. 4 shows that the inclination angle of the three projectiles decreases rapidly and eventually reverses, where the horizontal and vertical axes represent the time and inclination angles, respectively. The inclination angle of the cone changes from 15 to –7.3°, the ogive's changes from 15 to –9.3°, and the flat nose's changes from 15 to –11.6°.

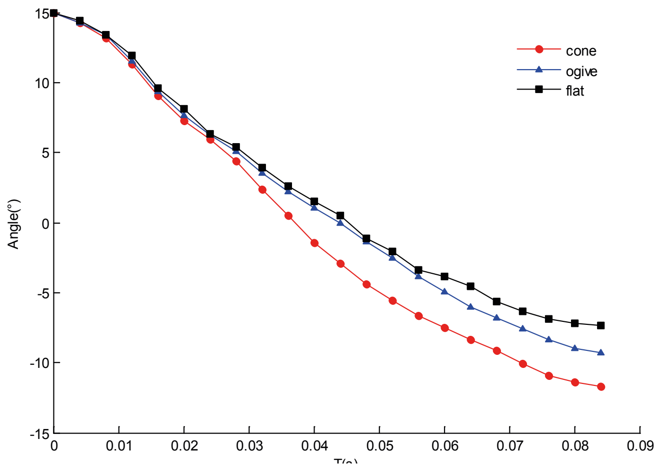


Fig. 4. The change in the inclination angle during the water-entry crossing process

Tables 4, 5, and 6 show the water-entry results and ricochet responses of the projectiles with cone, ogive, and flat noses, respectively.

Tab. 4. Experimental results of the cone nose

θ_i	V_i	θ_o	V_o	$\Delta\theta$	V_o/V_i
5	95.4	13.7	74.2	18.7	0.78
	123.1	14.3	93.4	19.3	0.76
	138.0	14.8	106.1	19.8	0.77
	156.4	15.6	124.8	20.6	0.80
	172.1	16.9	137.5	21.9	0.80
10	95.4	11.8	68.6	21.8	0.72
	123.1	13.0	81.0	23.0	0.66
	138.0	13.8	94.9	23.8	0.69
	156.4	15.3	114.8	25.3	0.73
	172.1	16.8	127.6	26.8	0.74
15	95.4	9.7	59.5	24.7	0.62
	123.1	11.6	73.7	26.6	0.60
	138.0	13.2	82.5	28.2	0.60
	156.4	14.7	97.9	29.7	0.63
	172.1	15.9	113.3	30.9	0.66
20	95.4	9.8	50.4	29.8	0.53
	123.1	11.9	55.8	31.9	0.45
	138.0	13.7	68.9	33.7	0.50
	156.4	15.1	85.7	35.1	0.55
	172.1	15.6	94.7	35.6	0.55
25	138.0	11.8	52.6	36.8	0.38
	156.4	12.9	70.1	37.9	0.45
	172.1	13.8	81.2	38.8	0.47
30	156.4	10.0	49.0	40.0	0.31
	172.1	11.1	59.9	41.1	0.35
35	172.1	9.6	41.8	44.6	0.24

Tab. 5. Experimental results of the ogive nose

θ_i	V_i	θ_o	V_o	$\Delta\theta$	V_o/V_i
5	95.4	13.3	72.3	18.3	0.76
	123.1	13.8	87.3	18.8	0.71
	138.0	14.5	98.1	19.5	0.71
	156.4	15.0	120.3	20.0	0.77
	172.1	15.7	135.3	20.7	0.79
10	95.4	11.7	63.9	21.7	0.67
	123.1	12.8	76.6	22.8	0.62
	138.0	13.1	87.6	23.1	0.64
	156.4	15.2	106.2	25.2	0.68
	172.1	15.7	123.8	25.7	0.72
15	95.4	9.6	55.4	24.6	0.58
	123.1	11.5	65.1	26.5	0.53
	138.0	12.9	77.1	27.9	0.56
	156.4	14.8	94.5	29.8	0.60
	172.1	15.6	104.7	30.6	0.61
20	123.1	11.8	53.1	31.8	0.43
	138.0	13.5	62.6	33.5	0.45
	156.4	14.7	78.0	34.7	0.50
	172.1	15.0	85.6	35.0	0.50
25	138.0	11.4	48.2	36.4	0.35
	156.4	12.4	68.2	37.4	0.44
	172.1	13.4	74.0	38.4	0.43
30	156.4	9.6	43.5	39.6	0.28
	172.1	10.6	53.2	40.6	0.31
35	172.1	8.8	37.2	43.8	0.22

Tab. 6 Experimental results of the flat nose

θ_i	V_i	θ_o	V_o	$\Delta\theta$	V_o/V_i
5	95.4	13	68.8551169	18.0	0.72
	123.1	13.6	79.5146777	18.6	0.65
	138.0	14.2	94.2377236	19.2	0.68
	156.4	14.7	117.924519	19.7	0.75
	172.1	15.5	131.686384	20.5	0.77
10	95.4	11.5	64.8496946	21.5	0.68
	123.1	12.8	70.1600098	22.8	0.57
	138.0	12.9	80.0261781	22.9	0.58
	156.4	15.1	101.659069	25.1	0.65
	172.1	15.6	118.775954	25.6	0.69
15	95.4	9.52	46.729927	24.5	0.49
	123.1	11.4	55.3894814	26.4	0.45
	138.0	13	64.8487995	28.0	0.47
	156.4	15	78.1992835	30.0	0.50
	172.1	15.1	89.5123135	30.1	0.52
20	123.1	11.7	44.3115851	31.7	0.36
	138.0	13.1	55.1904677	33.1	0.40
	156.4	14.1	67.2513838	34.1	0.43
	172.1	14.5	80.9053602	34.5	0.47
25	138.0	11.2	46.9118975	36.2	0.34
	156.4	12	60.9954411	37.0	0.39
	172.1	12.9	68.8556257	37.9	0.40
30	156.4	8.53	42.2276131	38.5	0.27
	172.1	9.26	48.198938	39.3	0.28
35	172.1	8.58	30.9850316	43.6	0.18

Note that when the incident angle is 20° and the initial velocity is 95.4 m/s, the results of the projectiles with the three nose-types are different, reflecting the ricochet behaviour of the cone-type projectiles, while the other two do not jump out of the water. In order to eliminate accidental influences, the water-entry experiment with the three types of projectiles heads was carried out under these conditions, and the experimental results were found to be the same as before, indicating that the results are normal.

Fig. 5 shows that the angle change data (*Y axis*) are interlaced at the same incident angle (*X axis*); however, overall, the data of the flat nose is below the ogive, and the ogive is below the flat nose under the same initial conditions, where the horizontal and vertical axes represent incident angles and angle changes, respectively. The angle change increases with the increasing incident angle, exhibiting a strong linear correlation. The relationship between the angle changes and incident angles is derived as follows:

$$\Delta\theta = 0.84\theta_i + 15.4 \tag{1}$$

According to the expression of the angle change, the relationship between the post-ricochet angle and the initial condition was obtained as follows:

$$\theta_o = 15.4 - 0.16\theta_i \tag{2}$$

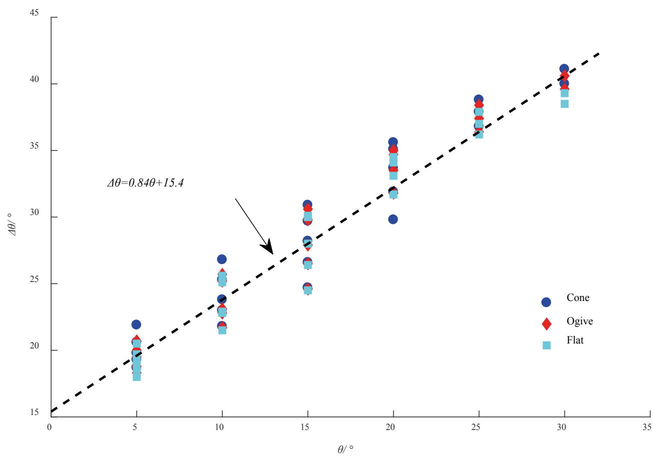


Fig. 5. The relationship between the incident angle and the angle change

Notably, when the incident angle is 0 and gravity is ignored, for a quality-determined and volume-ignoring projectile, the post-ricochet angle is 0 because the impact does not occur, and the angle change is 0 too. However, due to the existence of gravity, the negligible volume of the projectile, and the unevenness of the water–air interface, the projectile will inevitably interact with the water–air interface, changing the direction of motion. Therefore, the curve has a positive intercept on the vertical axis, and there is an incident angle such that the post-ricochet angle is equal to the incident angle.

After the projectile enters the water, the velocity will continue to decrease until it completely leaves the water. At the same initial velocity, when the projectile impacts on the water–air surface, the post-ricochet velocity is different due to the difference in the underwater trajectory and time. Fig. 6 shows the experimental results of the ratio of the residual velocity (*Y axis*) and the incident angle (*X axis*).

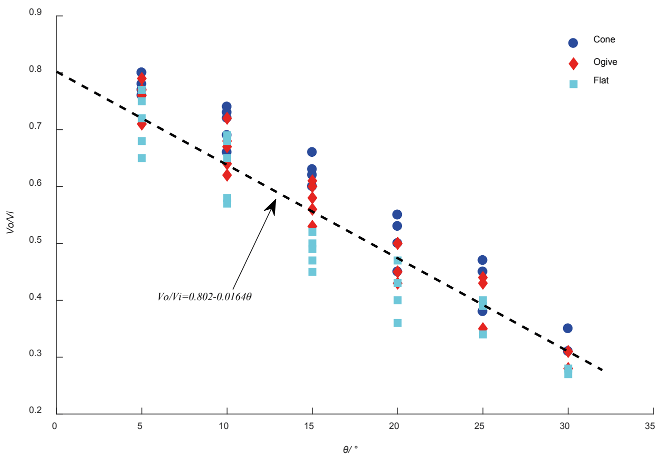


Fig. 6. The relationship between the incident angle and the ratio of the residual velocity

As the incident angle increases, the residual velocity of the projectile decreases, and eventually becomes insufficient to make the projectile jump out of the water. As shown in Fig. 6, a linear relationship was observed between the incident angle and the ratio of the residual velocity, fitted by the least square method and shown as follows:

$$\frac{V_o}{V_i} = 0.802 - 0.0164\theta_i \tag{3}$$

Similarly, when the incident angle is 0°, the projectile will inevitably interact with the water–air interface, and then change the original motion state; therefore, the ratio of the residual velocity is less than 1.

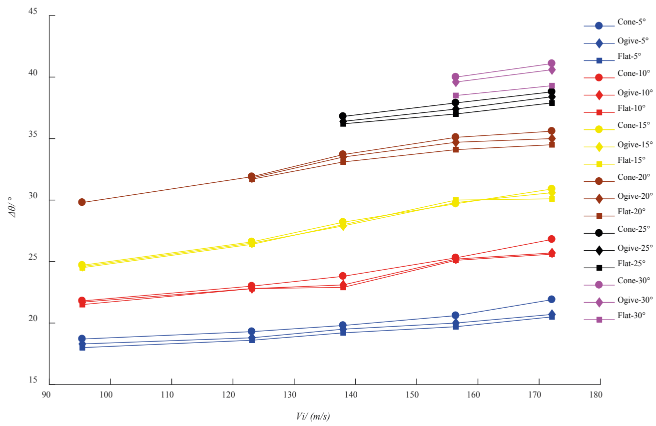


Fig. 7 The relationship between the initial velocity and the angle change

Fig. 7 shows the relationship between the angle change (*Y axis*) and the incident velocity (*X axis*) for projectiles with different nose-types, indicating that the angle change has a consistent trend with the initial velocity under different incident angles. As the incident velocity increases, the angle change increases, and the underwater trajectory stability becomes weak.

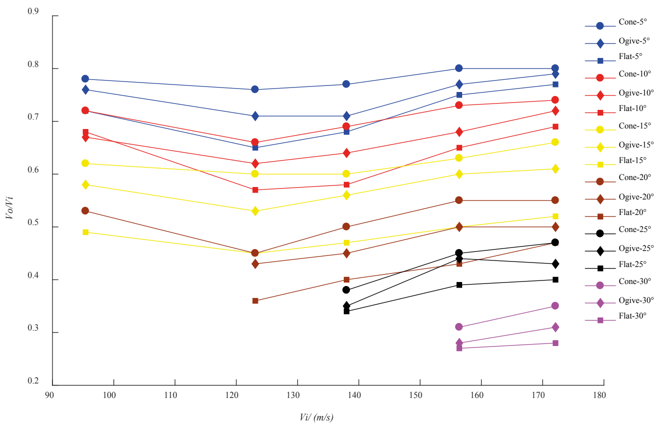


Fig. 8 The relationship between the initial velocity and the ratio of the residual velocity

Fig. 8 shows the relationship between the ratio of the residual velocity (*Y axis*) and the incident velocity (*X axis*), indicating that at the same incident angle, the ratio of the residual velocity will first decrease and then increase with the increasing initial velocity. The ratio of the residual velocity decreases for the three projectiles as the incident angle increases, mainly because the maximum depth of the centre of mass and the path experienced underwater increase, making the projectile consume a lot of kinetic energy to overcome the hydrodynamics.

Figs. 5–8 show that the cone projectile has a higher post-ricochet velocity and angle compared to the other two projectiles under the same initial conditions, indicating that a projectile with a cone nose has a weaker ability to maintain a straight trajectory when entering the water, has poor trajectory stability and is more prone to ricochet.

CONCLUSIONS

In conclusion, the ricochet behaviour during the water-entry crossing was experimentally investigated, and the variation in the displacement and inclination angle was analysed. The angle change and the ratio of the residual velocity are defined to describe the ricochet ability and trajectory stability, respectively. Water-entry tests were carried out under different initial conditions, and the post-ricochet velocity and angle were obtained. Based on this, the relationship between the ricochet response and the initial conditions was obtained. The experimental results of this study lead to the following conclusions: (1) The underwater trajectory of the projectiles with all three nose-types is bent upwards, and the motion parameters change basically. With the increasing nose apex angle (from cone, ogive to flat), the trajectory stability increases, and the more pointed the nose of the projectile is, the more likely that ricochet behaviour will occur. (2) With increasing incident angle, the angle change increases, and the ratio of the residual velocity decreases. By fitting the experimental data, the expressions of the post-ricochet velocity and angle were obtained. (3) At the same incident angle, the angle change increases with increasing initial velocity. At the same initial velocity, the ratio of the residual velocity decreases with increase of the incident angle.

Notably, the results only apply to the specific circumstances studied. Changing variables such as the slenderness ratio, density, and centroid position may affect the post-ricochet angle and velocity. In the next step, its applicability to other types of vehicles and other initial conditions will be investigated.

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