ASEN 2803 Lab 1: Pilot Simulator

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Abstract

Consider making a preliminary design of a re-configurable roller coaster that will be used for pilot training. Assume the train is brought to the top of the hill with a certain lift force, and the ride begins. Assume that opposing forces such as friction, air resistance, and uneven mass distribution are negligible effects such that the train is modeled as a point mass. The project's main objective is to sketch several FBDs and analyze the dynamics and design of specific track elements such as the loop, zero-G parabola, banked turns, and braking section. Each section will be assessed by the shapes, speed (height dependent), and G's force. Upon completion, the roller coaster will be assembled with each specific element, including transition phases. The equations governing the loop, parabola, and banked turns, each will be accounting for forces in several locations such as up/down, front/back, and lateral. These equations will subsequently be integrated into MATLAB via three plots. Thereafter, analyze overall track performance. Eventually, this project will be the basis for analyzing and producing a design for a roller coaster-based pilot training program.

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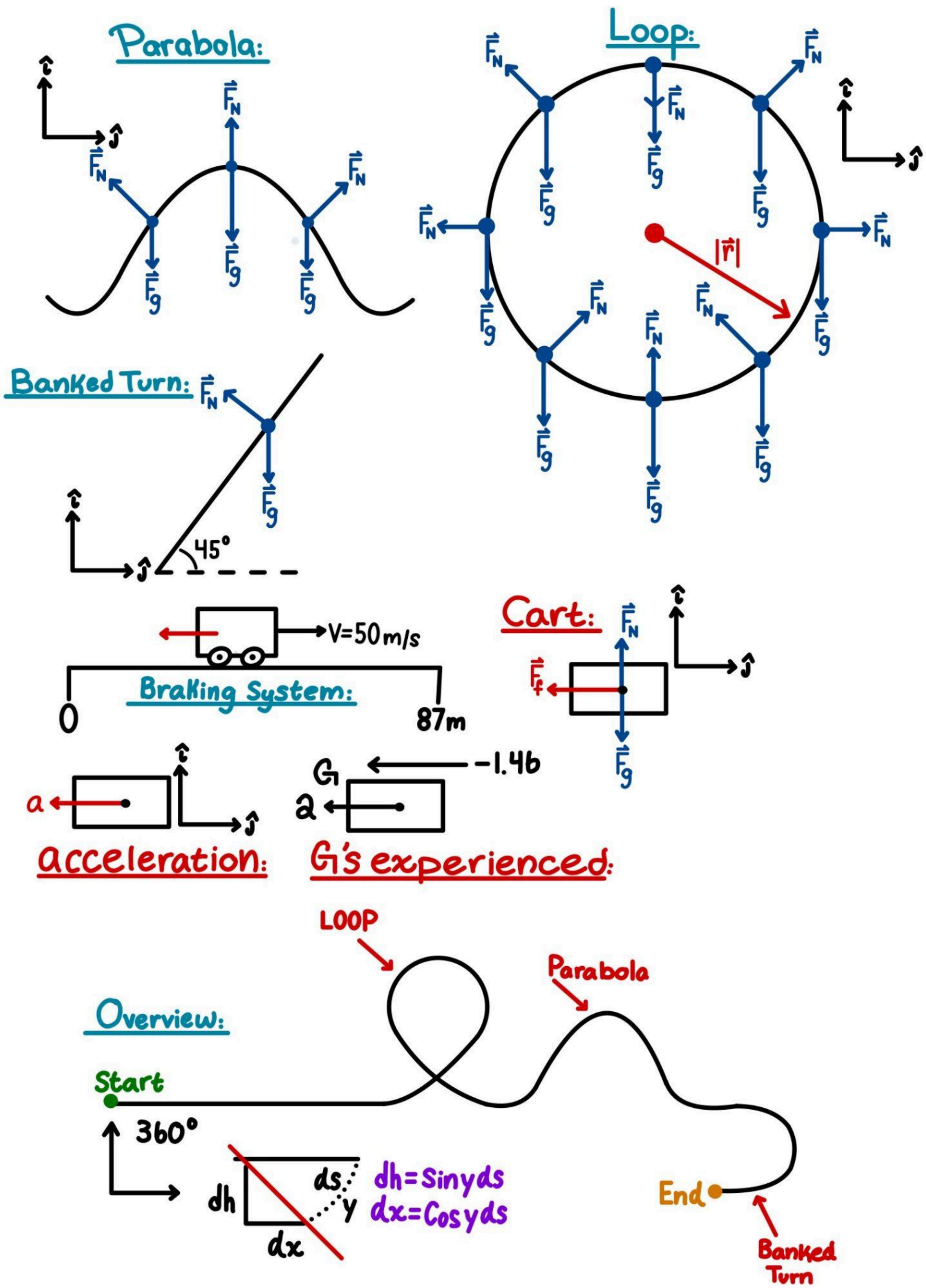
FBD Sketch



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Fundamental Equations:

$$v = \sqrt{2g(h_0 - h)} \rightarrow (\mathrm{I})$$

Loop:

$$y = r - rcos(\frac{s}{r}) \rightarrow (2)$$

$$x = rsin(\frac{s}{r}) \rightarrow (3)$$

$$\theta = tan^{-1}(\frac{sin(\frac{s}{r})}{cos(\frac{s}{r} + \frac{\pi}{2})}) \rightarrow (4)$$

$$G - Force_{Top} = \frac{v^2}{gr} - 1 \rightarrow (5)$$

$$G - Force_{Bottom} = \frac{v^2}{gr} + 1 \rightarrow (6)$$

$$G - Force_{\theta} = \frac{v^2}{gr} - sin(\frac{s}{r}) \rightarrow (7)$$

$$G - Force_{Side} = \frac{v^2}{gr} \rightarrow (8)$$

Banked Turns:

$$G_{force} = \frac{-v^2}{gr} + sin\theta \rightarrow (9)$$

$\frac{N}{mg} = \frac{-v^2}{gr} + sin\theta \rightarrow$ **Normal component** $\rightarrow (10)$

$\frac{L}{mg} = G_{force} \rightarrow$ **Lateral component** $\rightarrow (11)$

$$\frac{v^2}{rgsin\theta} = \frac{-v^2}{gr} + sin\theta \rightarrow (12)$$

$$\frac{1}{cos\theta} = \frac{N}{mg} = G_{force} \rightarrow (13)$$

$$tan(\theta) = \frac{v^2}{gr} \rightarrow (14)$$

$$r = \frac{v^2}{gtan(\theta)} \rightarrow (15)$$

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Parabola:

$$x(t) = \left|v_0\right| cos\theta_0 t \rightarrow (16)$$

$$y(t) = \left|v_0\right| sin\theta_0 t - \frac{gt^2}{2} \rightarrow (17)$$

$$s = \int_0^{\frac{2v_0 sin\theta}{g}} \sqrt{(x(t)^2 + y(t)^2} \, dt \rightarrow (18)$$

$$s(t) = \int_0^t \sqrt{(x(t)^2 + y(t)^2} \, dt \rightarrow (19)$$

$$G(s) = 0 \rightarrow (20)$$

Braking Section:

$$\Sigma F_x : f_f = -ma - (21)$$

$$\Sigma F_y : \mathrm{N} = \mathrm{mg} - (22)$$

$$\text{G-force} = 1 - (23)$$

$$s = v_1 t + \frac{1}{2} a t^2 - (24)$$

Discussion:

Overview:

Our track starts with a 45° angle from 125 m into a transition section, so the coaster is level at 100 m. The coaster then goes into the loop, the parabola, and a 90° banked turn, with all of these features starting and ending at the same altitude of 100 m. The coaster then goes down a 45° slope until the altitude reaches zero meters, and then brakes apply until its speed reaches to 0 m/s.

Transition section:

All but one of the transition sections in the rollercoaster are sections of circles. This has made it simple and easy to calculate G-forces throughout the transition sections. The location of each transition is located at the bottom of the initial ramp into the loop, one going into the parabola, and one going out of the parabola and into the banked section of five transition sections. There is also a constant slope going from the parabola to the banked turn.

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Loop:

The roller coaster's loop section begins at 100 meters and increases in height until it reaches 115 meters at its highest point. The loop diameter is 15 meters. The G-forces experienced through the rider's seat are up/down, at 5.9 and 3.3 G's, respectively. Through displacement of path length, the loop can have no lateral G's, as we are letting it self-intersect, but as our loop will exit through a section of the loop, no lateral Gs will be accounted for.

Parabola:

After the transition section out of the loop, the coaster continues through another transition section, with its lowest point being at 100m. The coaster then leaves the transition section at a predetermined angle. The G-forces throughout the parabola are zero in every direction, meaning that the speed and angle determine the shape of the parabola out of the transition section. After the coaster completes its trajectory, it goes into another transition section so that the coaster ends up at 100 m altitude.

Banked Turn:

The banked turn is considered the last portion of the coaster ride which follows the zero-G parabola. We will consider a few of the design parameters before proceeding with the bank turns and it is defined by some track elements like the speed of the coaster determined by the height difference, inclined angle, and G-force. The force component acting on the coaster would likely be lateral G's, Normal G's, and vertical downwards due to the weight component. We are to determine the values for each component so that the net force felt by a person sitting on the coaster would be zero I.e. "Balanced force". A person sitting on the train will feel force sideways but in this case, we are assuming the lateral force concerning the person's position is zero.

Braking Section:

In the braking section, the roller coaster comes from banked turns and starts to decelerate to a stop with a constant deceleration, using the Kinematics Equation (24) to determine the distance traveled along the track. The deceleration produces a forward/ backward G-force on the passengers so the passengers will feel a force pushing them backward to the direction of travel. The up/down G-force remains at 1G because the normal force acting only on the track exactly balances gravitational force, and since the braking section is horizontal there is no lateral g-force.

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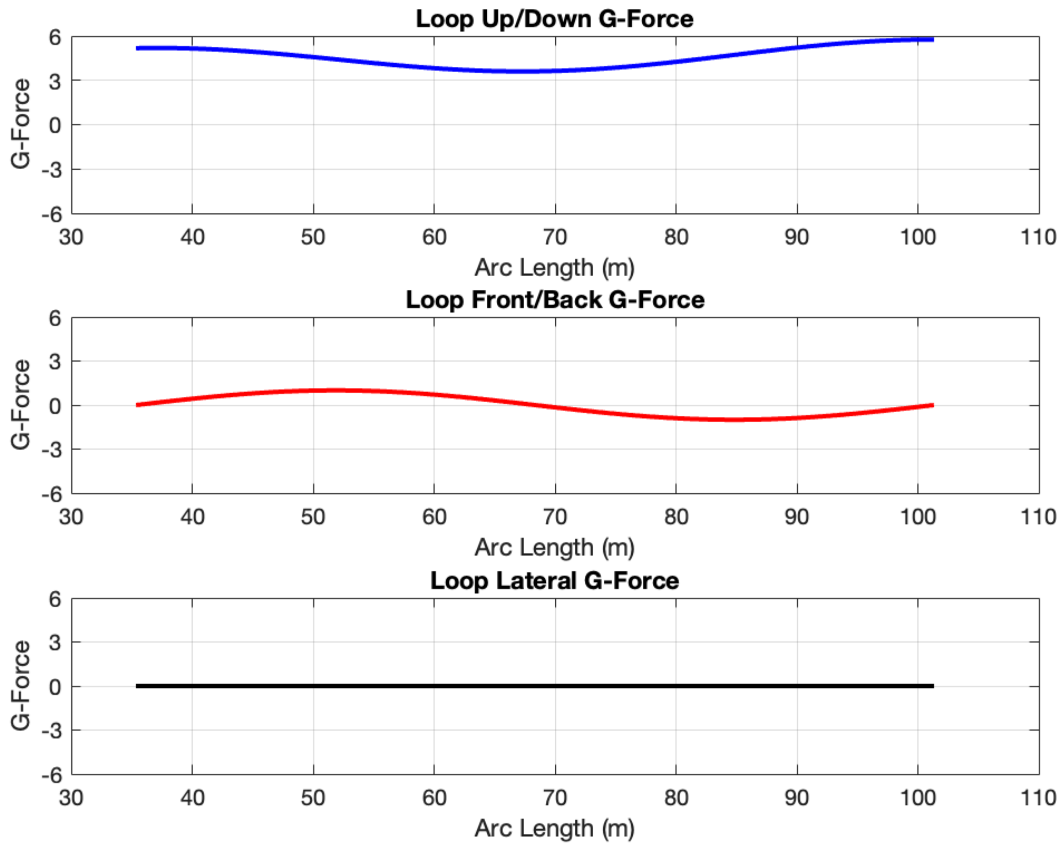
Performance Analysis (each element):

Loop:



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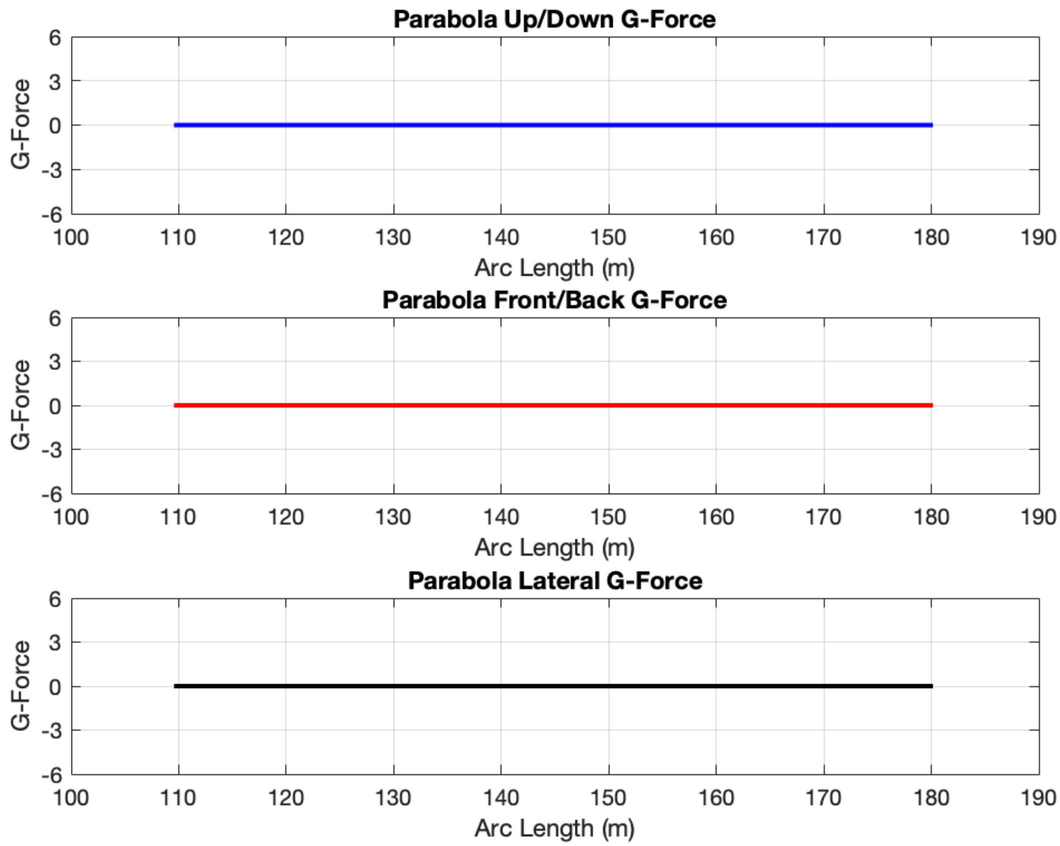
Parabola:

Using initial velocity from the height (22.14 m/s) and the initial angle which we set from the transition (pi/4) we can use simple kinematic projectile motion equations ((14) and (15)) to model the path, and integrate along the parabola ((16) and (17)) to find the arc length. Since projectile motion is only subject to gravity, there will be no normal force and therefore no Gs in any direction.



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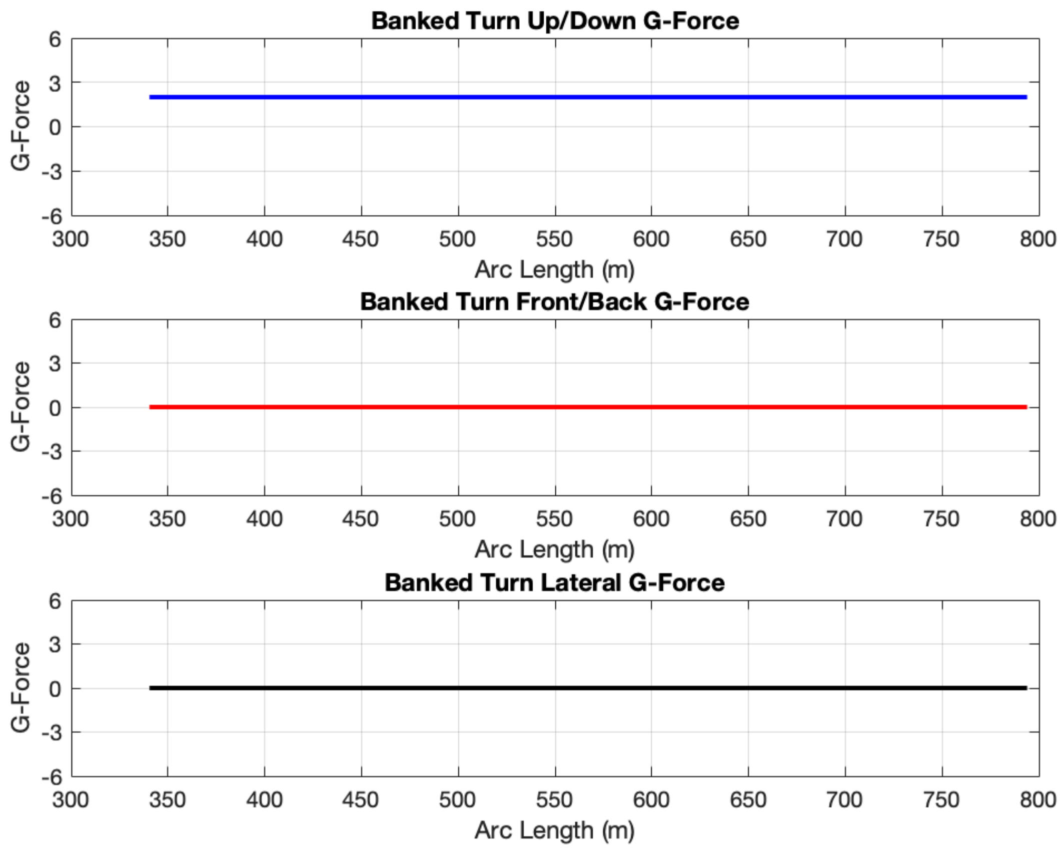
Banked Turn:

Assuming no lateral force, we can set a given bank angle and calculate the radius and G-force using (10) and (13). For our track, we set an angle of 60 degrees, giving a 144m radius and a G-force of 2.



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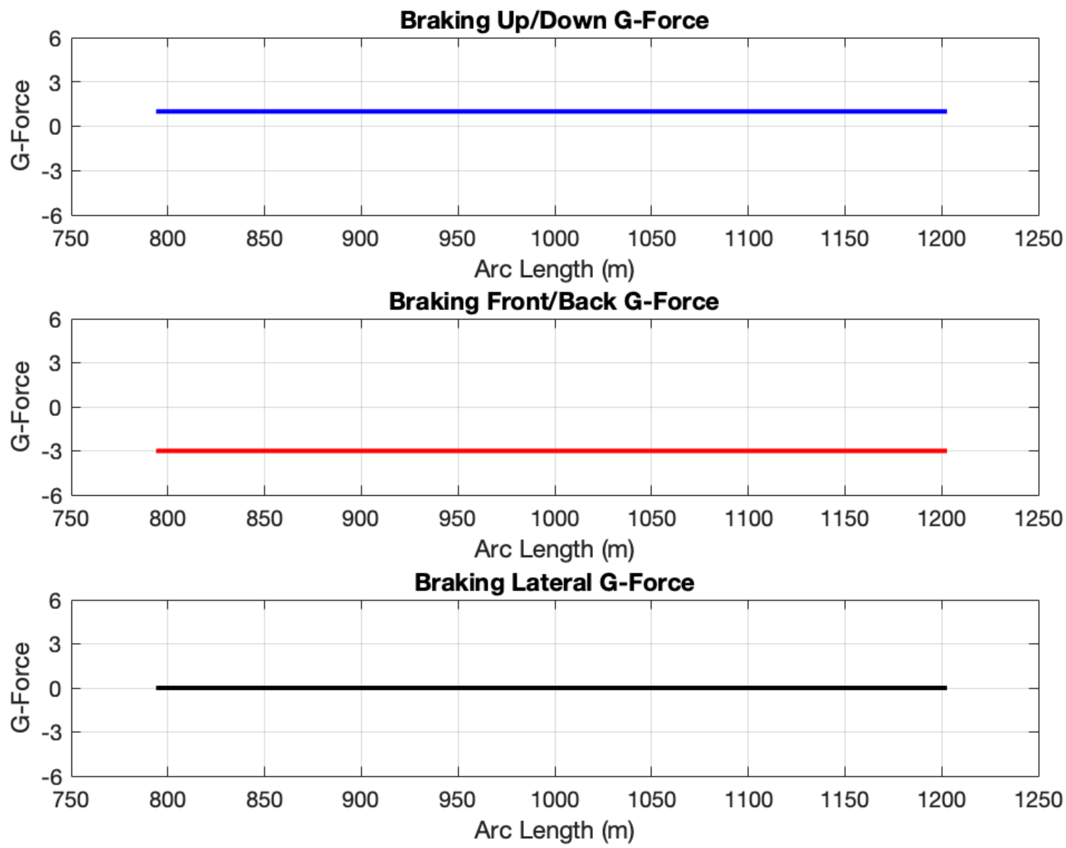
Braking Section:

The braking section starts with a velocity of 49.5 m/s and it is designed to reduce the train's speed from 50 to 0 m/s using a constant braking force of 3 G's. We chose this number as it was less than the 4 G's limit and still kept our coaster under the 1250m limit. Using this initial velocity and acceleration, we find the displacement under braking to be 408.75m



Performance Analysis (Full Coaster)

Whole Coaster:

Throughout the whole coaster, the maximum G-Force in each direction is the following:

Up - 5.9020
Down - 0
Front - 1
Back - 3
Lateral - 0

The whole coaster is designed to have frictionless wheels, balanced net force with constant

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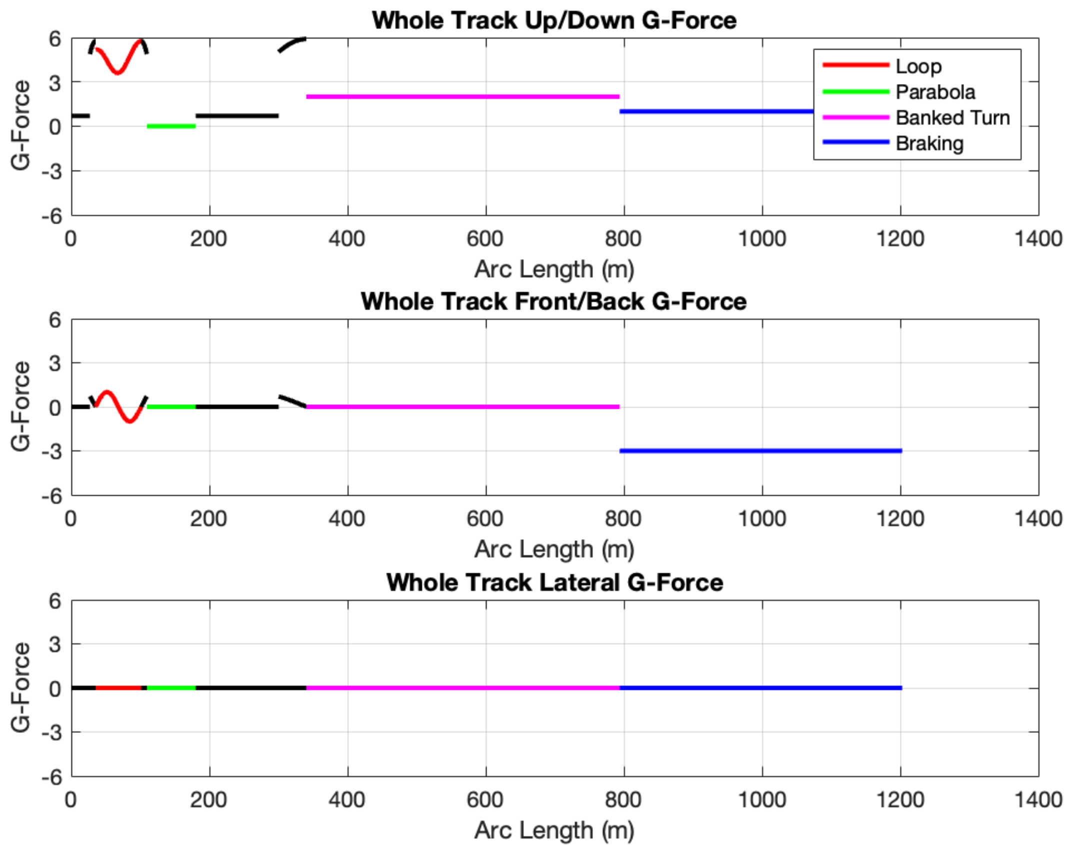
acceleration until the braking system is applied to stop the coaster and zero lateral force along the banked turn. The maximum speed of the coaster is dependent on the height of the coaster at which the ride begins and experienced G's force over the course of time is mass dependent. The circular transitions are the same derivation as the loop, so calculating the G-Force was simple after that was completed. The constant-slope transitions are also simple, with the only normal force being $mgcos(\theta)$.



Conclusions and Recommendations

Our first track segment is a constant downward slope, then a loop, followed by a parabola, then another constant downward slope into a banked turn, and finishes with the breaking section. Transition segments are either circles or a constant descent, allowing for simple modeling of forces.

There are many assumptions that we made in this model. For one, we assumed a coaster to have a frictionless track, which isn't ideal in a real-world scenario. The frictional force would

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cause loss of kinetic energy into other forms resulting in the change of velocity and therefore G-Force across the entire track is affected. Also, we modeled the car as a point mass, meaning all rotational effects are neglected. These are mostly valid assumptions for a preliminary coaster design, except in the banked turn. In the banked turn, we assumed it to be an ideal case with no lateral force acting on a body. The coaster moves with a constant velocity for the entire track time until the braking system is applied to stop it that leads to deceleration. The loop was also only in one plane, meaning that the coaster is going through itself and a self-intersecting loop would not apply to real life. There are also other considerations that our simple model has not taken into account, like the structure and foundation needed to support the coaster.

Some recommendations that could be made are about coaster tracks with friction, banked turns where lateral force is assumed to be zero for this lab assignment but it is actually not in a real world scenario and consideration of that would have resulted in different outcomes.

Member Contributions

Abdullah Alshehri (worked on the derivations for the braking section, wrote the code for the braking section, and also worked on writing the lab document)

Anil Ambrosi (Wrote main MATLAB code, derivations for parabola, performance analysis for parabola and full coaster)

Nicolas Andersen (Worked on the write-ups for the lab document. Also worked on the derivations for the transitions section.)

Nathan Geuzine (Completed Loop Derivations, Loop Code, Loop Performance, Revised and completed Abstract, Revised all FBDs, and contributed to various parts of the report.)

Ritik Sarraf (Completed the Abstract, Completed Conclusion and Recommendations, Completed Performance Analysis (Full Coaster), Discussion (Banked Turn), Fundamental Equations (Banked Turn), Provided Ideologies for all FBDs, References, Partial Banked Turn Code.)

Acknowledgments

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2. "Free Body Diagrams on a Loop-the-Loop Roller Coaster."

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3. "Roller Coaster Design."

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Appendix I: Published MATLAB Code

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Table of Contents


```
clc;clear;close all;
```

constant givens

```
h0 = 125;
g = 9.81;
```

start the coaster on a downhill slope of pi/4

```
r1 = 10.5;
s1f = 25*sqrt(2)-(pi/4)*r1;
s1 = linspace(0,s1f);

G1_U = cos(pi/4)*ones(1,numel(s1));
G1_F = 0.*s1;
G1_L = 0.*s1;
```

transition from slope into bottom of loop

```
s2f = s1f + (pi/4)*r1;
s2 = linspace(s1f,s2f);
s2_adj = s2-s1f;

theta2 = s2_adj./r1;
h2 = 125 - (100 + r1*(1-cos((pi/4) - theta2)));
v2 = sqrt(2*g*h2);

G2_U = (v2.^2)./(g*r1) + cos((pi/4) - theta2);
G2_F = sin((pi/4) - theta2);
G2_L = 0.*s2;
```

loop

```
s3f = s2f+2*pi*r1;
s3 = linspace(s2f,s3f);
s3_adj = s3-s2f;

theta3 = s3_adj./r1;
h3 =  125 - (100 + r1*(1-cos(theta3)));
v3 = sqrt(2*g*h3);

G3_U = (v2.^2)./(g*r1) + cos(theta3);
G3_F = sin(theta3);
G3_L = 0.*s3;
```

loop to parabola

```
s4f = s3f+.25*pi*r1;
s4 = linspace(s3f,s4f);
s4_adj = s4-s3f;

theta4 = s4_adj./r1;
h4 =  125 - (100 + r1*(1-cos(theta4)));
v4 = sqrt(2*g*h4);

G4_U = (v4.^2)./(g*r1) + cos(theta4);
G4_F = sin(theta4);
G4_L = 0.*s3;
```

parabola

```
theta5 = pi/4;
h5 = 125 - (100 + r1*(1-cos(theta5)));
v5 = sqrt(2*g*h5);

func_s_p = @(t) sqrt((v5*cos(theta5).*t).^2+(v5*sin(theta5).*t-9.81.*(t.^2)/
2).^2);
s_p = integral(func_s_p,0,2*v5*sin(theta5)/9.81);

s5f = s4f + s_p;
s5 = linspace(s4f, s5f);

G5_U = 0.*s5;
G5_F = 0.*s5;
G5_L = 0.*s5;
```

transition out of parabola, linear portion

```
r6 = 51;
h_slope = 100-r6*(1-cos(pi/4));
s6f = s5f + h_slope*sqrt(2);
s6 = linspace(s5f,s6f);
```

```
s6_adj = s6-s5f;

G6_U = cos(pi/4).*ones(1,numel(s6));
G6_F = 0.*s6;
G6_L = 0.*s6;
```

transition out of parabola, circle portion

```
s7f = s6f + (pi/4)*r6;
s7 = linspace(s6f,s7f);
s7_adj = s7-s6f;

theta7 = s7_adj./r6;
h7 = 125 - r6*(1-cos((pi/4) - theta7));
v7 = sqrt(2*g*h7);

G7_U = (v7.^2)./(g*r6) + cos((pi/4) - theta7);
G7_F = sin((pi/4) - theta7);
G7_L = 0.*s7;
```

banked turn

```
theta8 = pi/3;
h8 = 125;
v8 = sqrt(2*g*h8);
r8 = cot(theta8)*(v8.^2)/g;

s8f = s7f + pi*r8;
s8 = linspace(s7f,s8f);

G8_U = (1/cos(theta8)) .* ones(1,numel(s8));
G8_F = 0.*s8;
G8_L = 0.*s8;
```

braking

```
h9 = 125;
v9i = sqrt(2*g*h9);
s_break = (v9i.^2)/(2*3);
s9f = s8f + s_break;
s9 = linspace(s8f,s9f);

G9_U = ones(1,numel(s9));
G9_F = -3*ones(1,numel(s9));
G9_L = 0.*s9;
```

plots

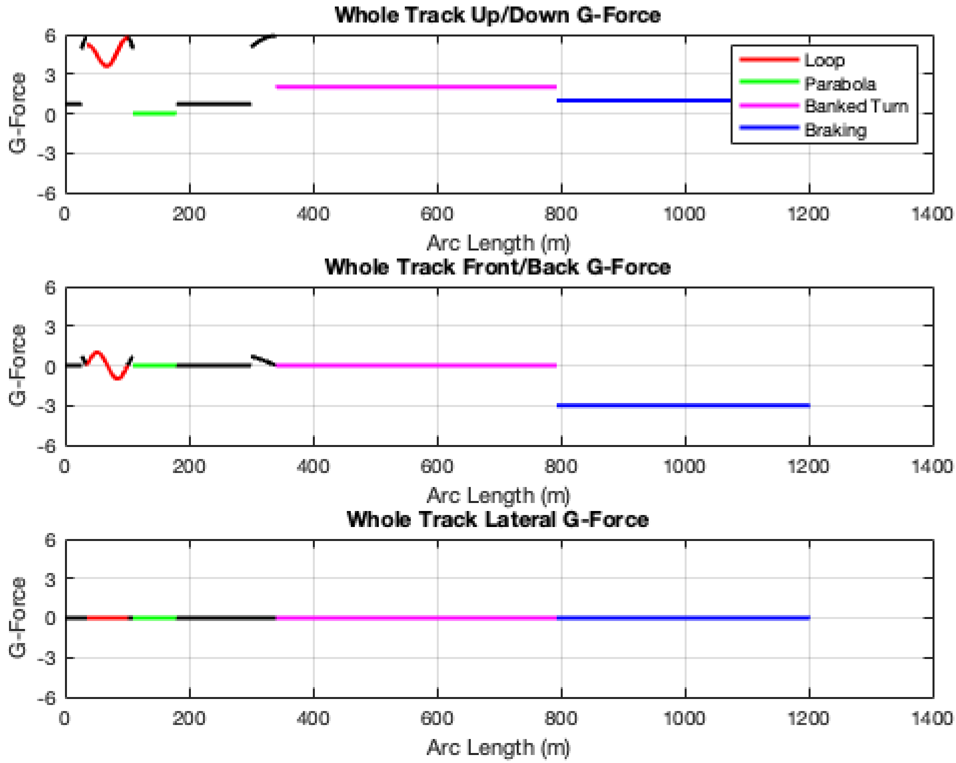
```
width = 2;

% whole track
```

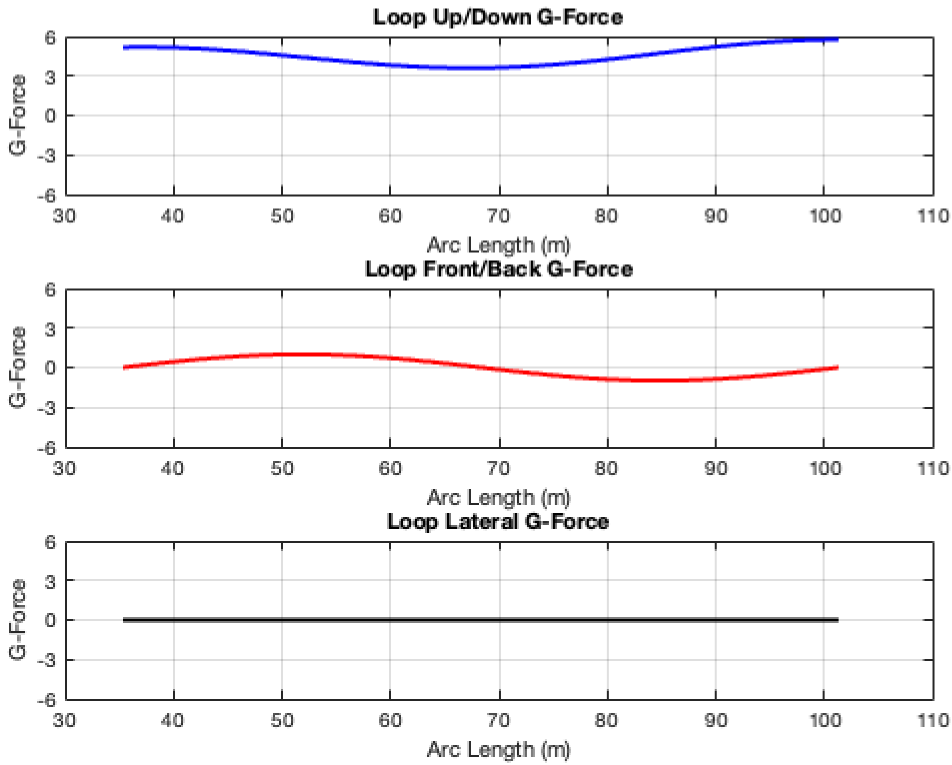
```
figure()
subplot(3,1,1)
plot(s1,G1_U,'black','LineWidth',width)
hold on
plot(s2,G2_U,'black','LineWidth',width)
p1 = plot(s3,G3_U,'red','LineWidth',width);
plot(s4,G4_U,'black','LineWidth',width)
p2 = plot(s5,G5_U,'green','LineWidth',width);
plot(s6,G6_U,'black','LineWidth',width)
plot(s7,G7_U,'black','LineWidth',width)
p3 = plot(s8,G8_U,'magenta','LineWidth',width);
p4 = plot(s9,G9_U,'blue','LineWidth',width);
title('Whole Track Up/Down G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on
legend([p1 p2 p3 p4],{'Loop', 'Parabola', 'Banked Turn', 'Braking'})


subplot(3,1,2)
plot(s1,G1_F,'black','LineWidth',width)
hold on
plot(s2,G2_F,'black','LineWidth',width)
plot(s3,G3_F,'red','LineWidth',width)
plot(s4,G4_F,'black','LineWidth',width)
plot(s5,G5_F,'green','LineWidth',width)
plot(s6,G6_F,'black','LineWidth',width)
plot(s7,G7_F,'black','LineWidth',width)
plot(s8,G8_F,'magenta','LineWidth',width)
plot(s9,G9_F,'blue','LineWidth',width)
title('Whole Track Front/Back G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,3)
plot(s1,G1_L,'black','LineWidth',width)
hold on
plot(s2,G2_L,'black','LineWidth',width)
plot(s3,G3_L,'red','LineWidth',width)
plot(s4,G4_L,'black','LineWidth',width)
plot(s5,G5_L,'green','LineWidth',width)
plot(s6,G6_L,'black','LineWidth',width)
plot(s7,G7_L,'black','LineWidth',width)
plot(s8,G8_L,'magenta','LineWidth',width)
plot(s9,G9_L,'blue','LineWidth',width)
title('Whole Track Lateral G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
```

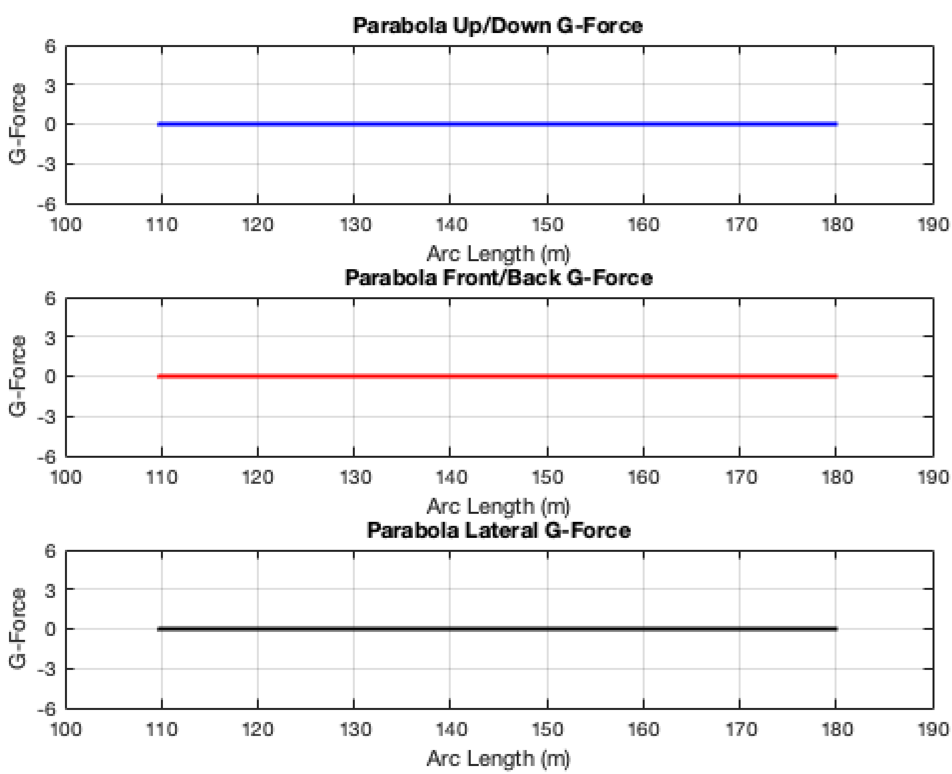
```
yticks([-6 -3 0 3 6])
grid on

%loop
figure()

subplot(3,1,1)
plot(s3,G3_U,'blue','LineWidth',width);
title('Loop Up/Down G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,2)
plot(s3,G3_F,'red','LineWidth',width);
title('Loop Front/Back G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,3)
plot(s3,G3_L,'black','LineWidth',width);
title('Loop Lateral G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

%parabola
figure()

subplot(3,1,1)
plot(s5,G5_U,'blue','LineWidth',width);
title('Parabola Up/Down G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,2)
plot(s5,G5_F,'red','LineWidth',width);
title('Parabola Front/Back G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on
```

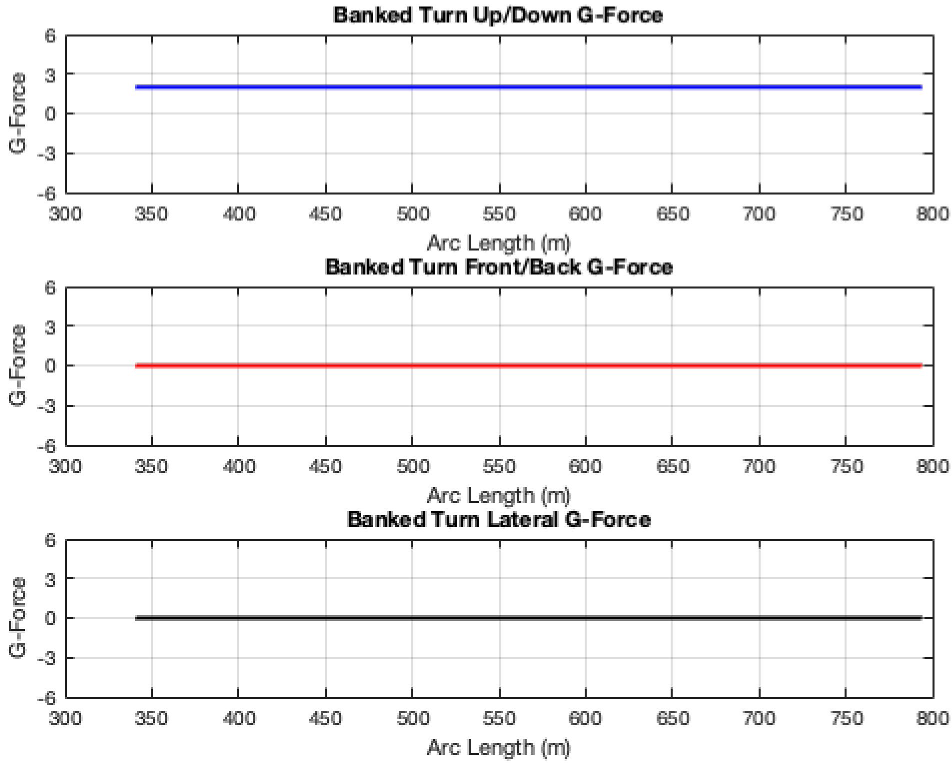
```
subplot(3,1,3)
plot(s5,G5_L,'black','LineWidth',width);
title('Parabola Lateral G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

%turn
figure()

subplot(3,1,1)
plot(s8,G8_U,'blue','LineWidth',width);
title('Banked Turn Up/Down G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,2)
plot(s8,G8_F,'red','LineWidth',width);
title('Banked Turn Front/Back G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,3)
plot(s8,G8_L,'black','LineWidth',width);
title('Banked Turn Lateral G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

%braking
figure()

subplot(3,1,1)
plot(s9,G9_U,'blue','LineWidth',width);
title('Braking Up/Down G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,2)
plot(s9,G9_F,'red','LineWidth',width);
title('Braking Front/Back G-Force')
```

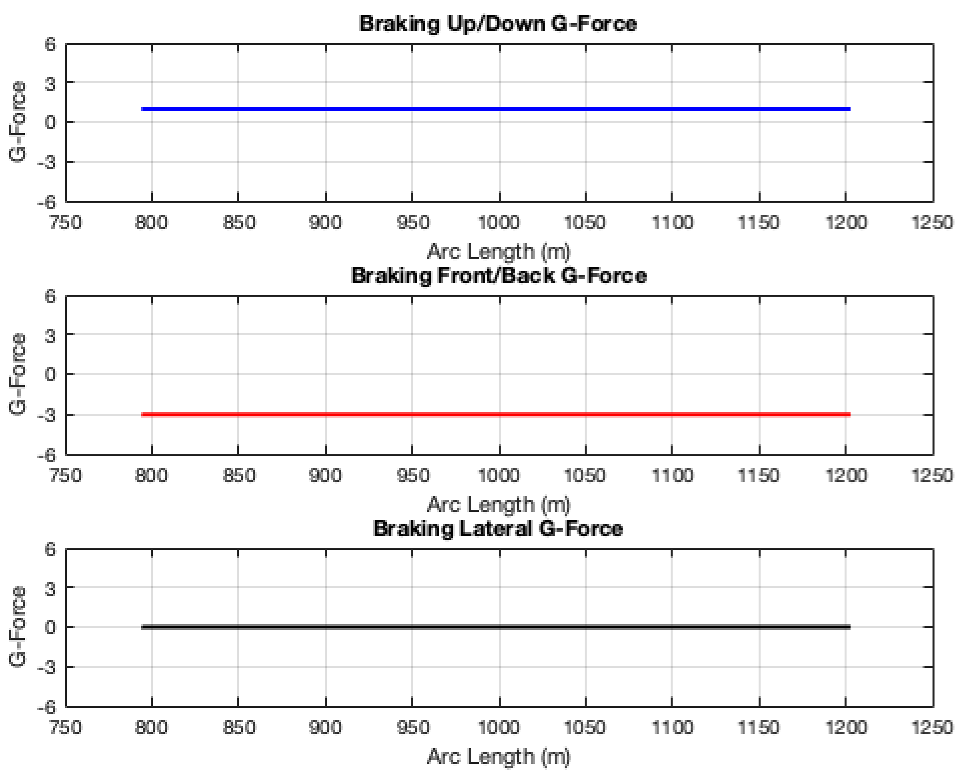
```
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on

subplot(3,1,3)
plot(s9,G9_L,'black','LineWidth',width);
title('Braking Lateral G-Force')
xlabel('Arc Length (m)')
ylabel('G-Force')
ylim([-6 6])
yticks([-6 -3 0 3 6])
grid on
```




Loop Up/Down G-Force
Loop Front/Back G-Force
Loop Lateral G-Force
G-Force
Arc Length (m)


Parabola Up/Down G-Force
Parabola Front/Back G-Force
Parabola Lateral G-Force
G-Force
Arc Length (m)


Banked Turn Up/Down G-Force
Banked Turn Front/Back G-Force
Banked Turn Lateral G-Force
G-Force
Arc Length (m)
6
3
0
-3
-6
300
350
400
450
500
550
600
650
700
750
800


Braking Up/Down G-Force
Braking Front/Back G-Force
Braking Lateral G-Force
G-Force
Arc Length (m)
6
3
0
-3
-6
750
800
850
900
950
1000
1050
1100
1150
1200
1250

maxes and mins

```
max_U = max([G1_U G2_U G3_U G4_U G5_U G6_U G7_U G8_U G9_U])
max_D = min([G1_U G2_U G3_U G4_U G5_U G6_U G7_U G8_U G9_U])
max_F = max([G1_F G2_F G3_F G4_F G5_F G6_F G7_F G8_F G9_F])
max_B = min([G1_F G2_F G3_F G4_F G5_F G6_F G7_F G8_F G9_F])
```

```
max_U =

    5.9020


max_D =

     0


max_F =

    0.9999


max_B =

    -3
```

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