Mathematical Models: Designing a Roller Coaster

Douglas Meade, Ronda Sanders and Xian Wu

Department of Mathematics

Overview

There are three objectives in this lab:

- understand the mathematical reasoning associated with a real-world example,
- learn to define a piecewise-defined function in Maple, and
- learn to set up and solve a system of equations in Maple.

Maple Essentials

Important Maple commands introduced in this lab are:

Command	Description
`diff`	`diff(F, x);` differentiate F in terms of x OR `diff(f(x), x);` if f is defined as a function.
`eval`	`eval(F, x=a);` evaluate F at $x = a$
`piecewise`	define a piecewise-defined function The general syntax to represent $\begin{cases} f_1, & cond_1 \\ f_2, & cond_2 \\ \vdots & \vdots \\ f_n, & cond_n \end{cases}$ is: `piecewise(` $cond_1$ `,` f_1 `,` $cond_2$ `,` f_2 `, ...,` $cond_n$ `,` f_n `);` where each $cond_i$ is an inequality and each f_i is an expression.

Maple does not recognize double inequalities, so if your condition is $a \le x < b$ you would write `x>=a and x<b`.

Preparation

Review properties of the first derivative.

Assignment

This week's mastery quiz asks you to solve a system of equations and graph a piecewise-defined function. The steps involved in solving this week's problem will help you with the questions on the mastery quiz.
Project 1 will be due at the *beginning* of next week's lab.

The Problem: Design a Roller Coaster

Suppose we are asked to design a simple ascent and drop roller coaster with an overall horizontal displacement of 200 feet. By studying pictures of our favorite roller coasters, we decide to create our roller coaster using a line, a parabola and a cubic. We begin the ascent along a line $y = f1(x)$ of slope 1.5 for the first 20ft horizontally. We continue the ascent and begin the drop along a parabola $y = f2(x) = ax^2 + bx + c$ for the next 100ft horizontally. Finally, we begin a soft landing at 30ft above the ground along a cubic $y = f3(x) = dx^3 + ex^2 + fx + g$ for the last 80ft.

Here are our tasks:

1. Find a system of 7 equations with the 7 unknowns ({a,b,c,d,e,f,g}) that will ensure that the track is smooth at transition points.
2. Solve the equations in (1) to find our functions. (We should get a unique solution as we have the same number of equations and unknowns.)
3. Plot the graph to see the design.
4. Find the maximum height of the roller coaster.

Solving the Problem

We begin by defining our functions in Maple. If we choose the origin as our starting point, our first function $y = f1(x)$ is a line of slope 1.5 that passes through (0,0), and we have:

```
> f1:=x-> 1.5*x;
> f2:=x-> a*x^2+b*x+c;
> f3:=x-> d*x^3+e*x^2+f*x+g;
```

We will also need the first derivatives of our functions. (If you do not see why, you will soon.) To find and assign the derivatives, right-click over the function and choose **differentiate**. Then right-click over the derivative function and choose **assign to a name**. Name the derivatives $df1, df2$, and $df3$, respectively.

Since our roller coaster consists of three curves, it can be set up mathematically as a piecewise-defined function:

$$F(x) = \begin{cases} f1(x), & 0 \le x \le 20 \\ f2(x), & 20 < x < 120 \\ f3(x), & 120 \le x \le 200 \end{cases}$$

We assign F in Maple as follows:

```
> F:=piecewise(x<=20, f1(x), x>20 and x<120, f2(x), x>=120 and x<=200, f3(x));
```

Obviously, we want $F(x)$ to be continuous (so our passengers do not perish). This means that our functions should be equal at transition points. So we get the following equations:

```
> eq1:=f1(20)=f2(20);
> eq2:=f2(120)=f3(120);
```

If we are to have a smooth track, we cannot have abrupt changes in direction, so the first derivative $F'(x)$ should also be continuous. That is, the first derivatives of our functions should also be equal at transition points. So we get:

```
> eq3:=df1(20)=df2(20);
> eq4:=df2(120)=df3(120);
```

To start our landing at 30ft above the ground for the last 80ft, we would have:

```
> eq5:=f3(120)=30;
```

Finally, in order to have a soft landing, the track should be tangent to the ground at the end:

```
> eq6:=f3(200)=0;
> eq7:=df3(200)=0;
```

We now have a system of 7 equations and 7 unknowns. We solve using the `solve` command and assign the solutions as follows:

```
> values:=solve({eq1,eq2,eq3,eq4,eq5,eq6,eq7} , {a,b,c,d,e,f,g});
```

You can now view and differentiate $F(x)$:

```
> F:=eval(F,values);
> dF:=diff(F,x);
```

We can see what our coaster looks like with the following `plot` command:

```
> plot(F, x=0..200, y=-50..150, discont=true);
```

Note: *The `discont=true` option will show us if the graph has any gaps or holes.*

To find the maximum height, find where the graph has a horizontal tangent line and evaluate $F(x)$ at each point. The largest is the maximum height of the coaster.

```
> solve(dF=0, x);
```