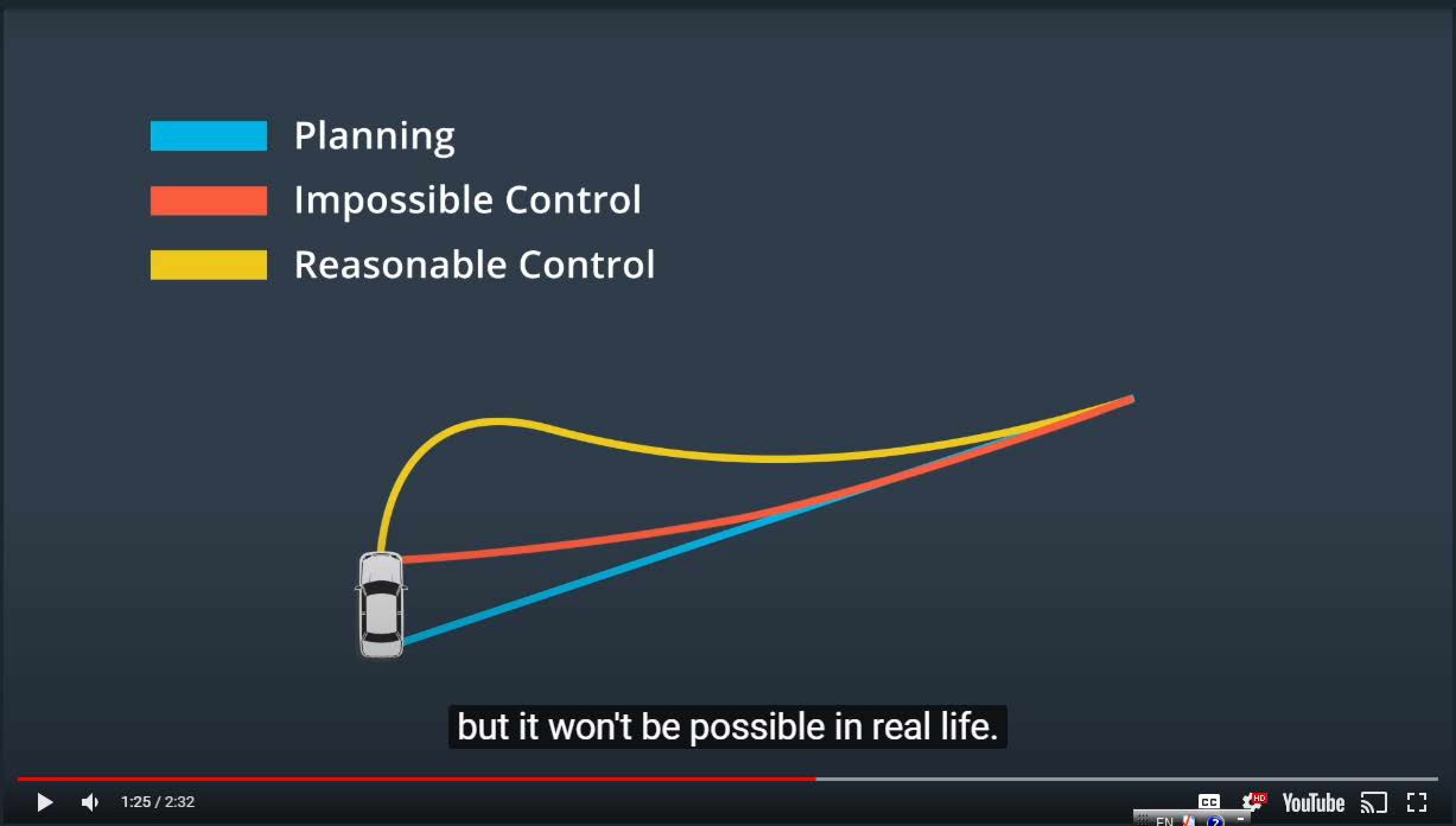
a control inputs to move the vehicle towards those way points.

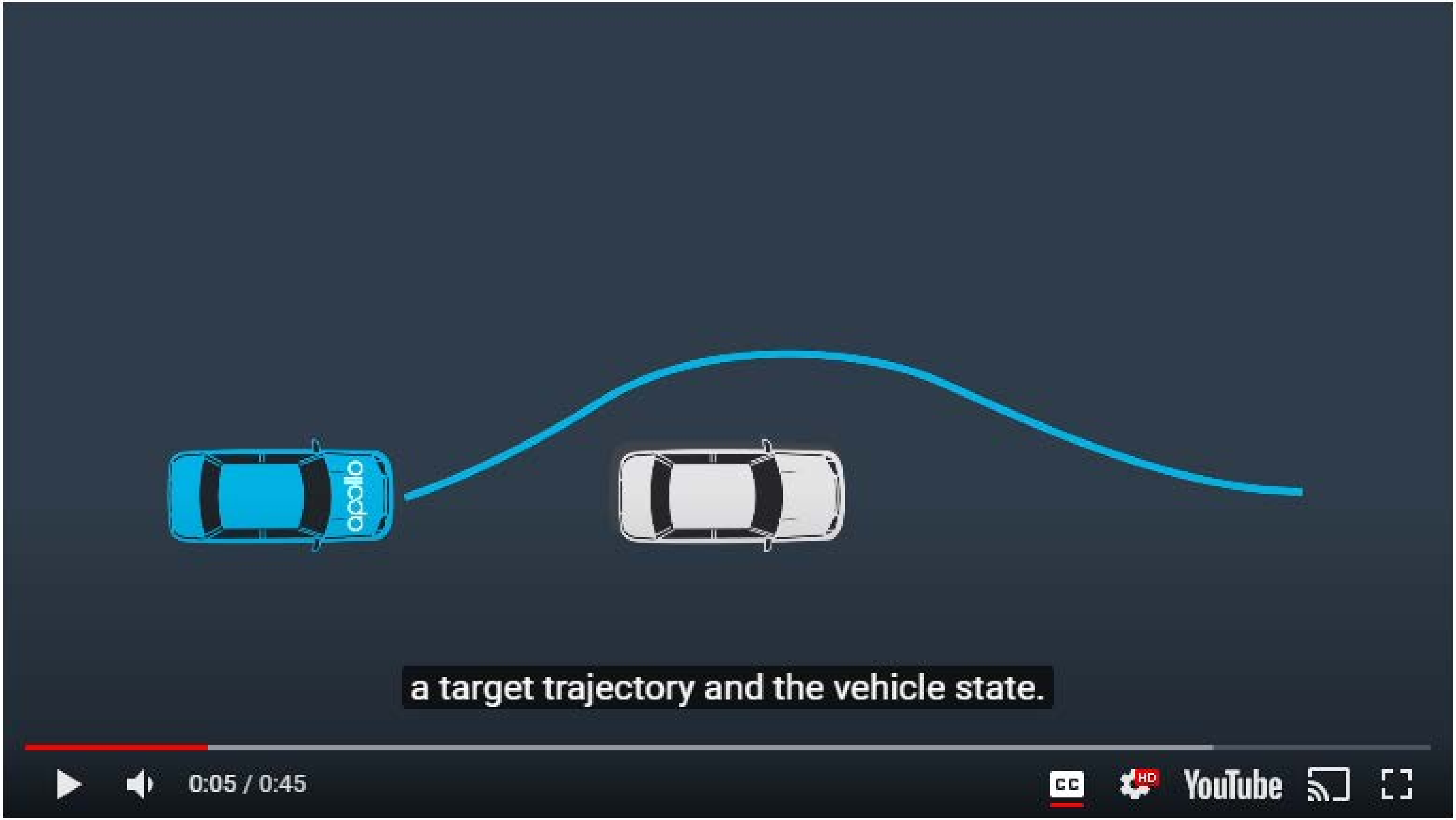

Planning
Result of Control
the controller still needs to execute the trajectory accurately.
1:07 / 2:32

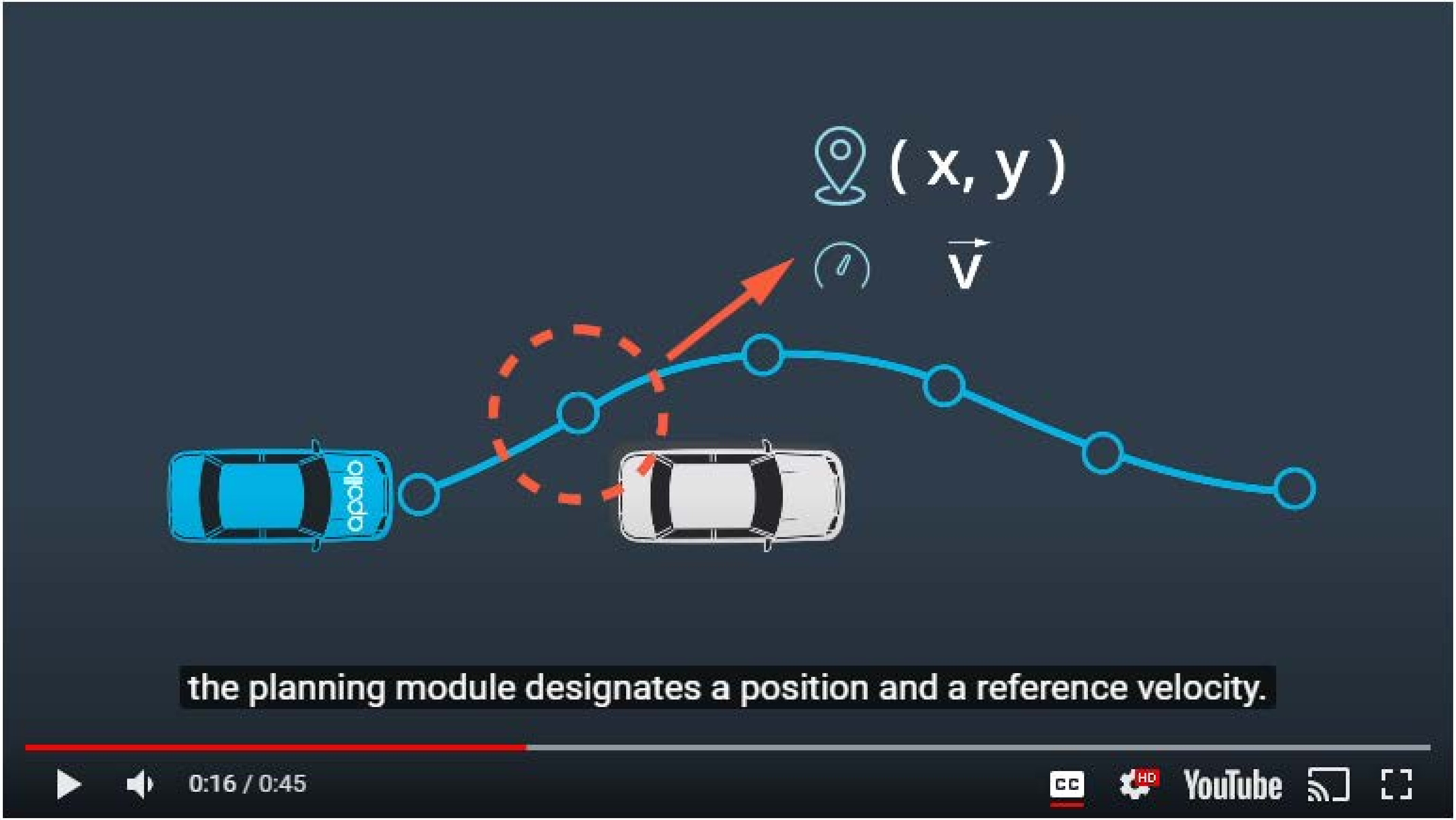

Planning
Impossible Control
Reasonable Control
but it won't be possible in real life.
1:25 / 2:32
YouTube

Which means you should avoid sudden steering, acceleration or break.

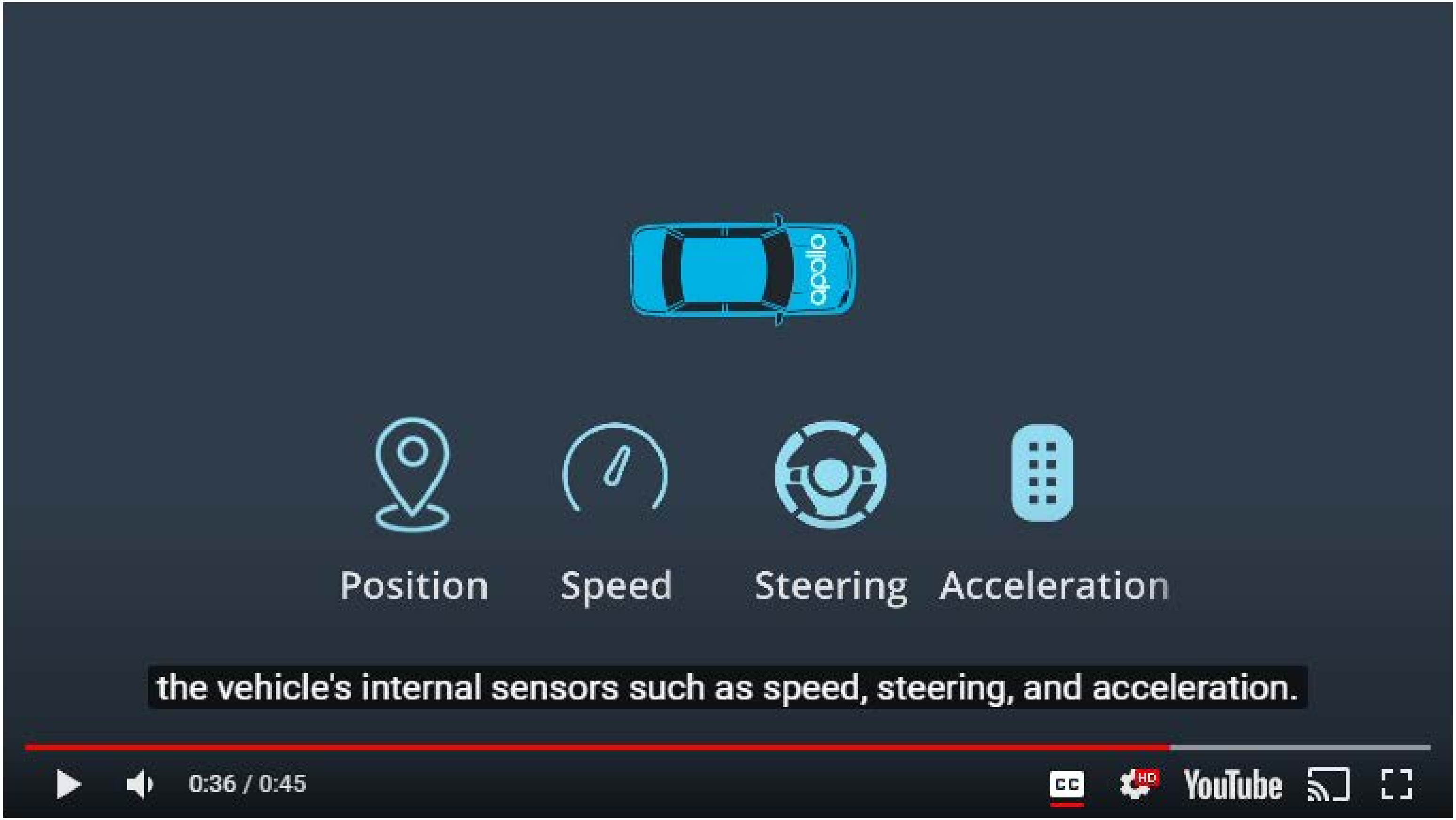

Planning
Control Maneuver
Lovely
To minimize deviation from target trajectory,
2:02 / 2:32


Planning
Control Maneuver
Lovely
and maximize passenger comfort.
2:05 / 2:32
YouTube

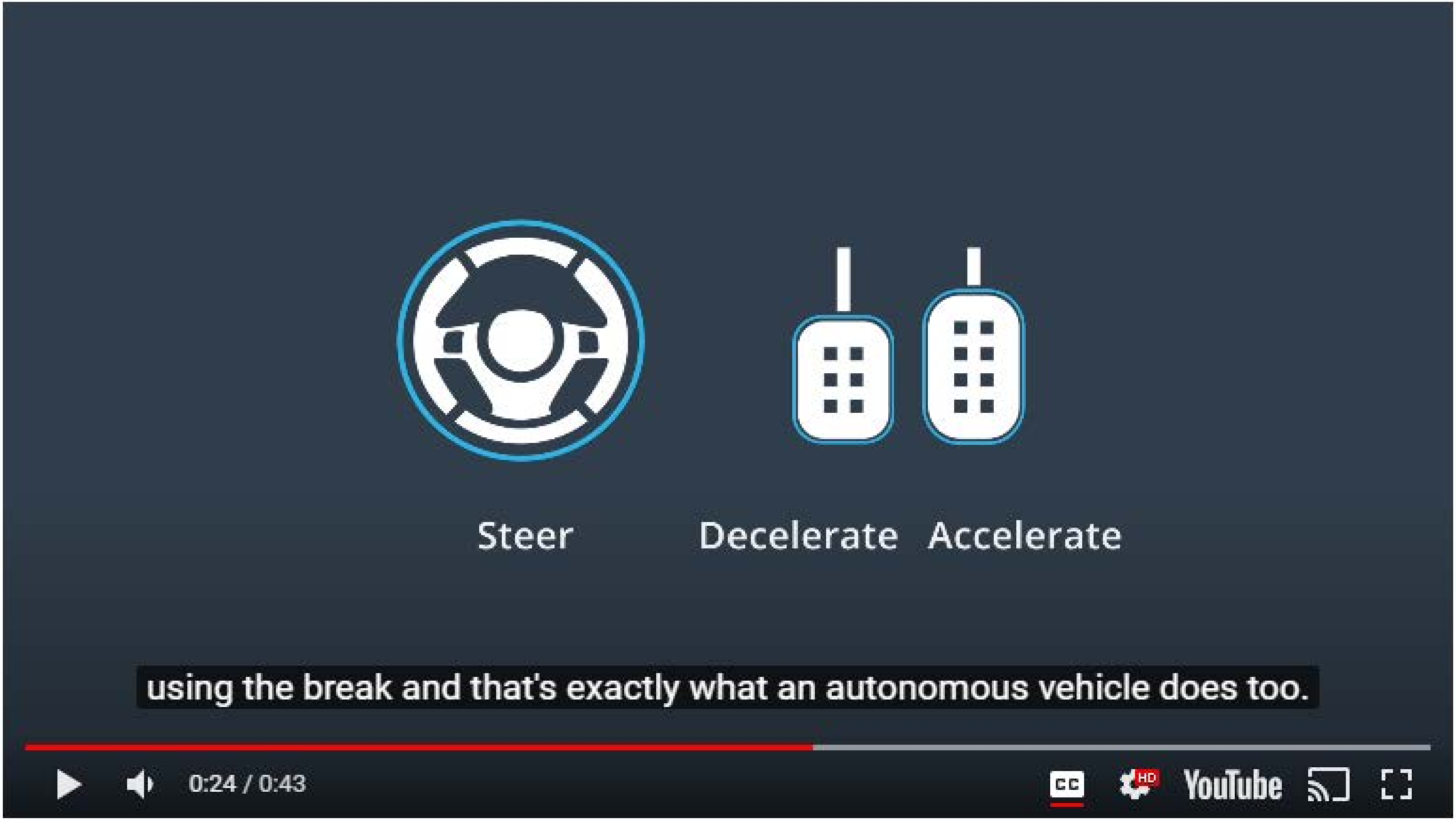

apollo
a target trajectory and the vehicle state.
0:05 / 0:45
HD
YouTube



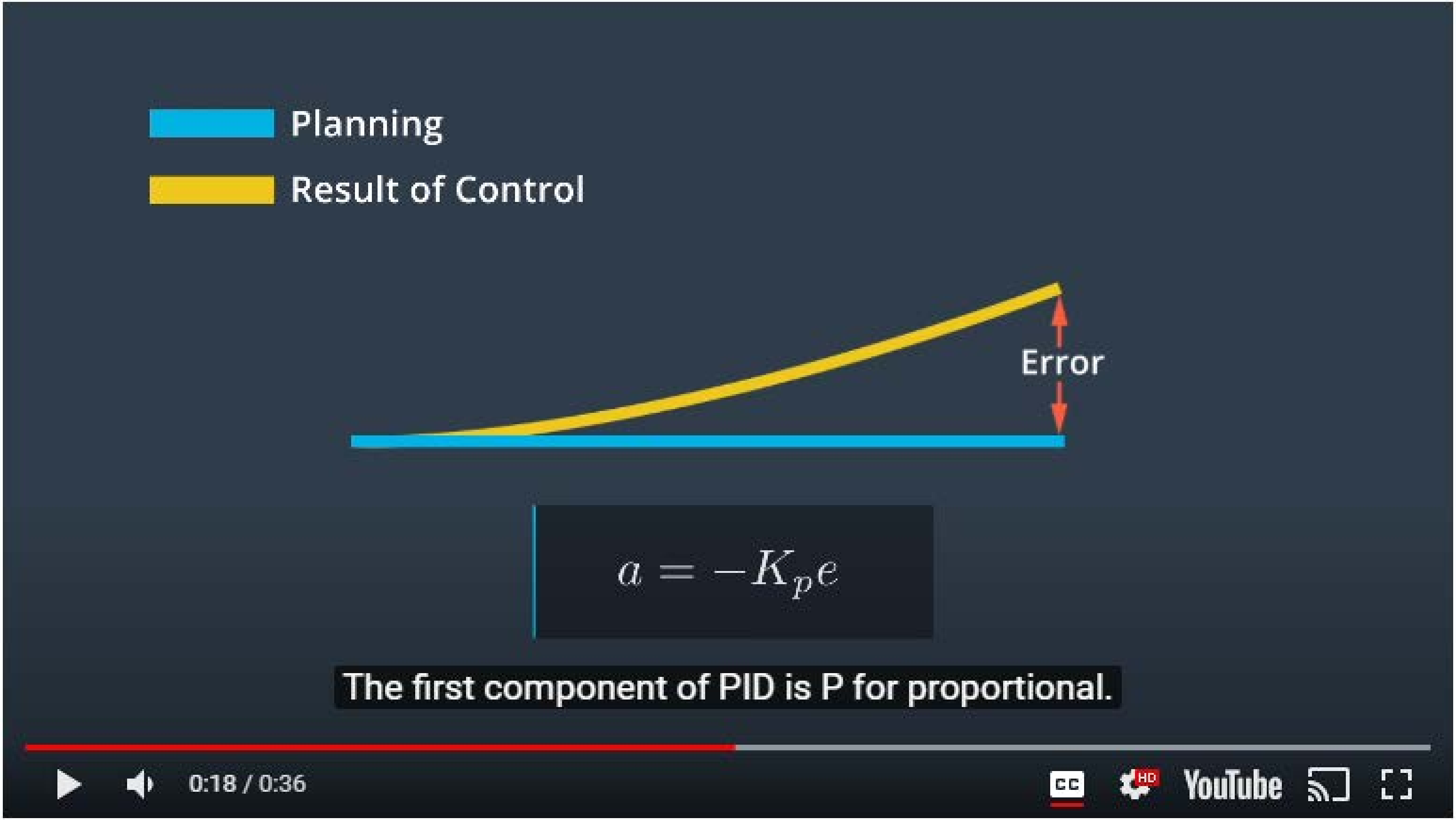
(x, y)
v
apollo
the planning module designates a position and a reference velocity.
0:16 / 0:45
HD
YouTube


apollo
Position
Speed
Steering
Acceleration
the vehicle's internal sensors such as speed, steering, and acceleration.
0:36 / 0:45
YouTube

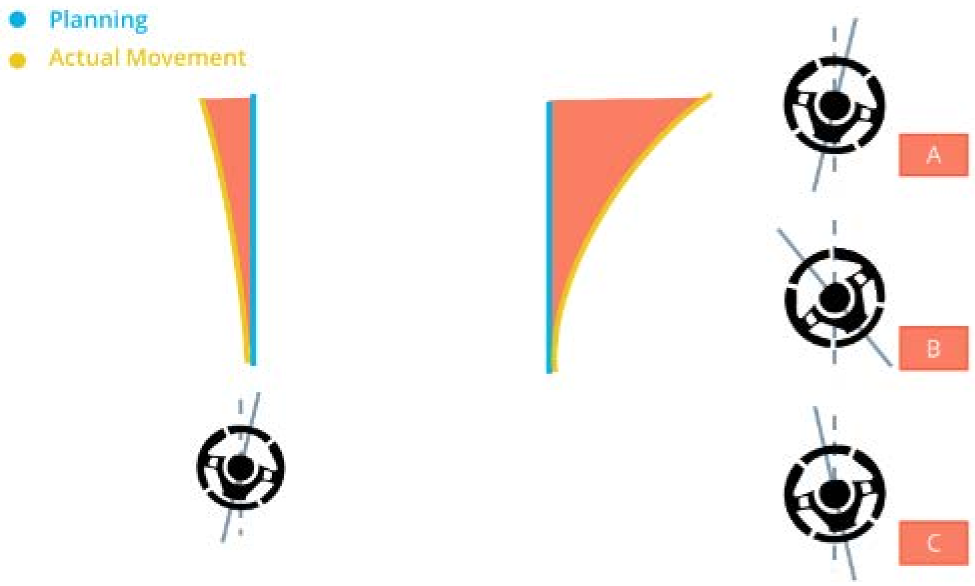

Right
we want to take action to correct this deviation.
0:12 / 0:43
YouTube


Steer
Decelerate
Accelerate
using the break and that's exactly what an autonomous vehicle does too.
0:24 / 0:43
HD
YouTube

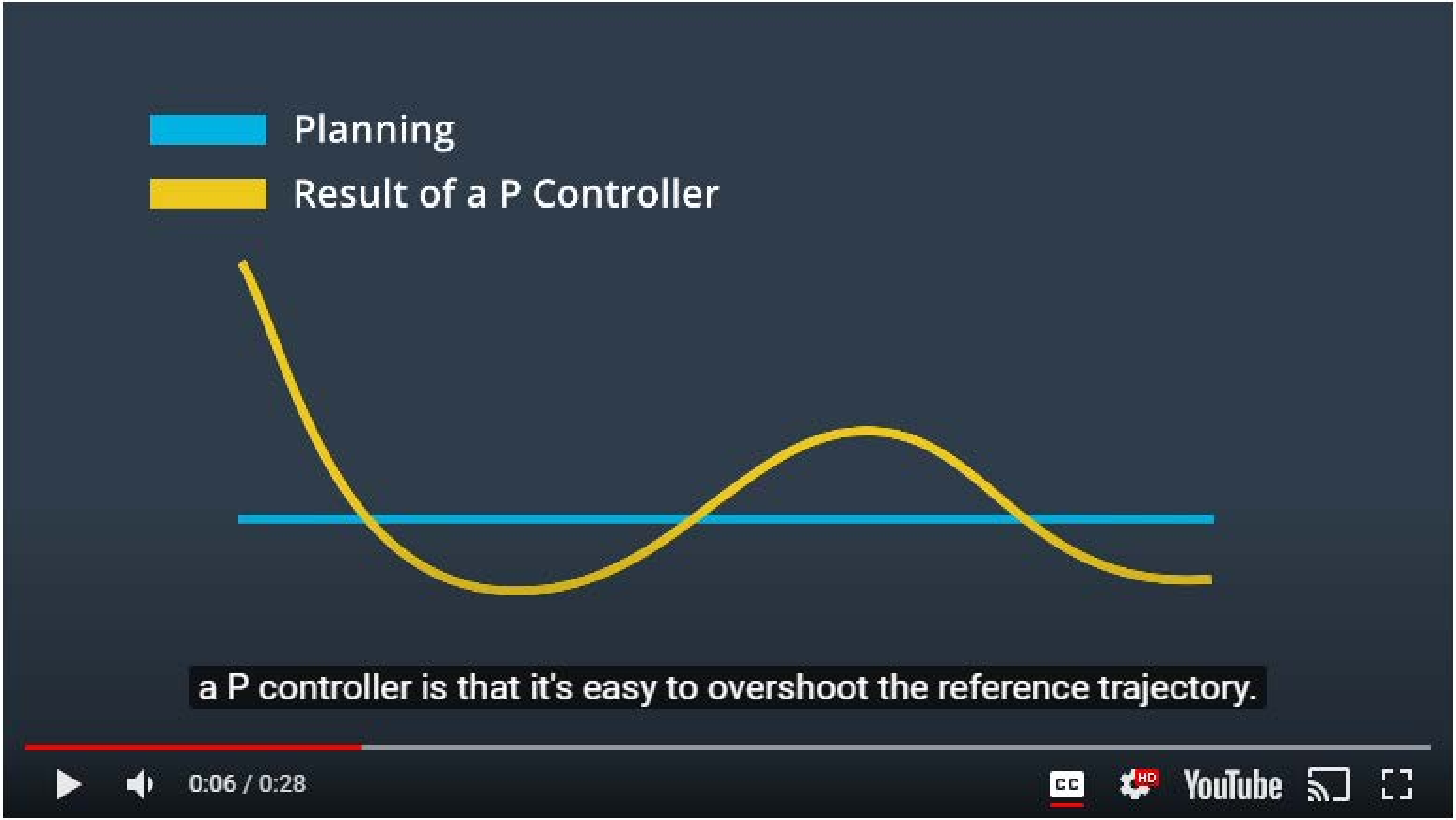

Planning
Result of Control
Error
All it needs to know is how far we have deviated from the target trajectory.
0:13 / 0:36
YouTube


Planning
Result of Control
Error
$a = -K_p e$
The first component of PID is P for proportional.
0:18 / 0:36
HD
YouTube

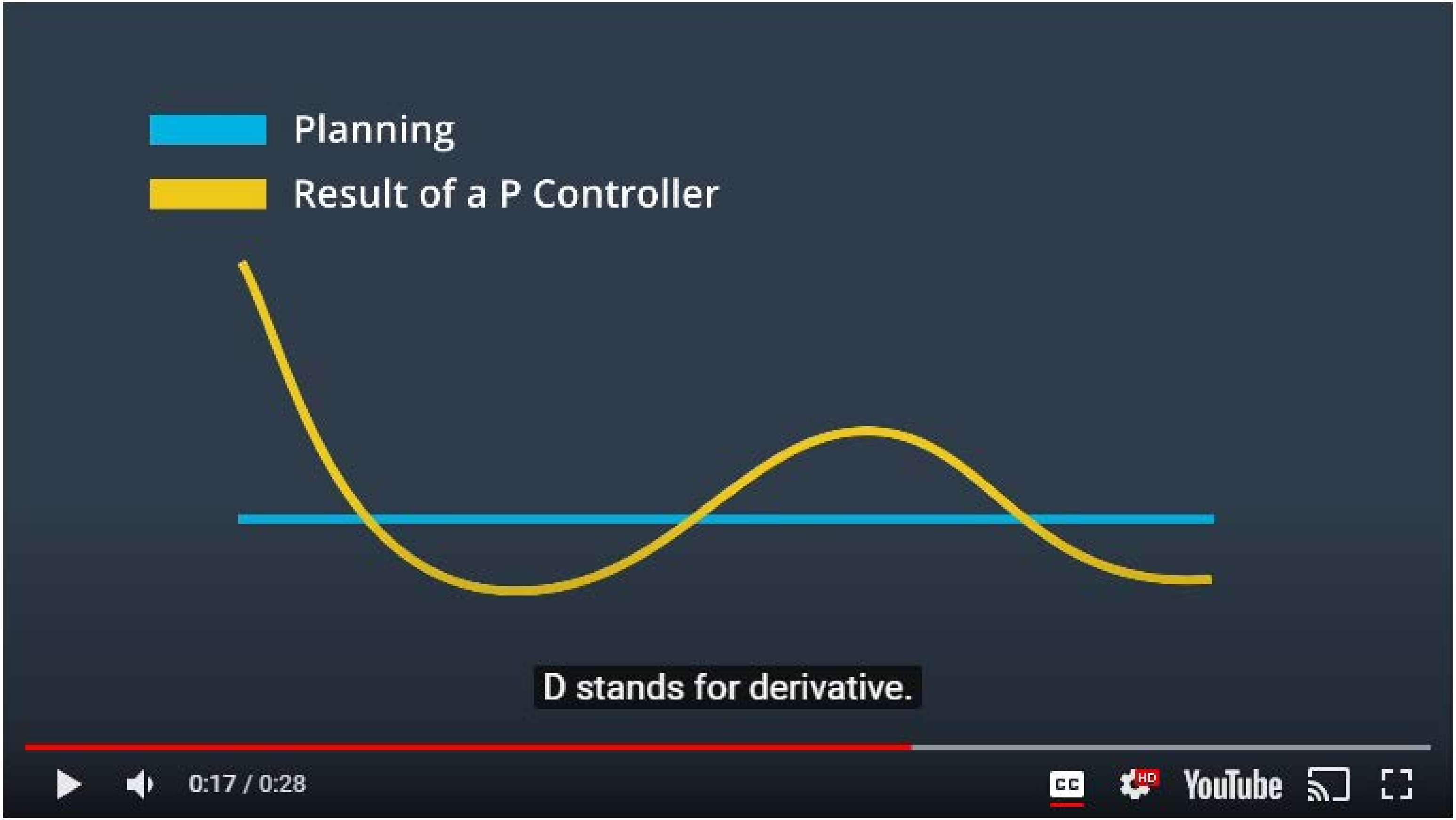
Suppose the picture on the left demonstrates the heading error and the steering angle provided by a P controller. For the error shown on the right, which steering angle will the controller will give ?

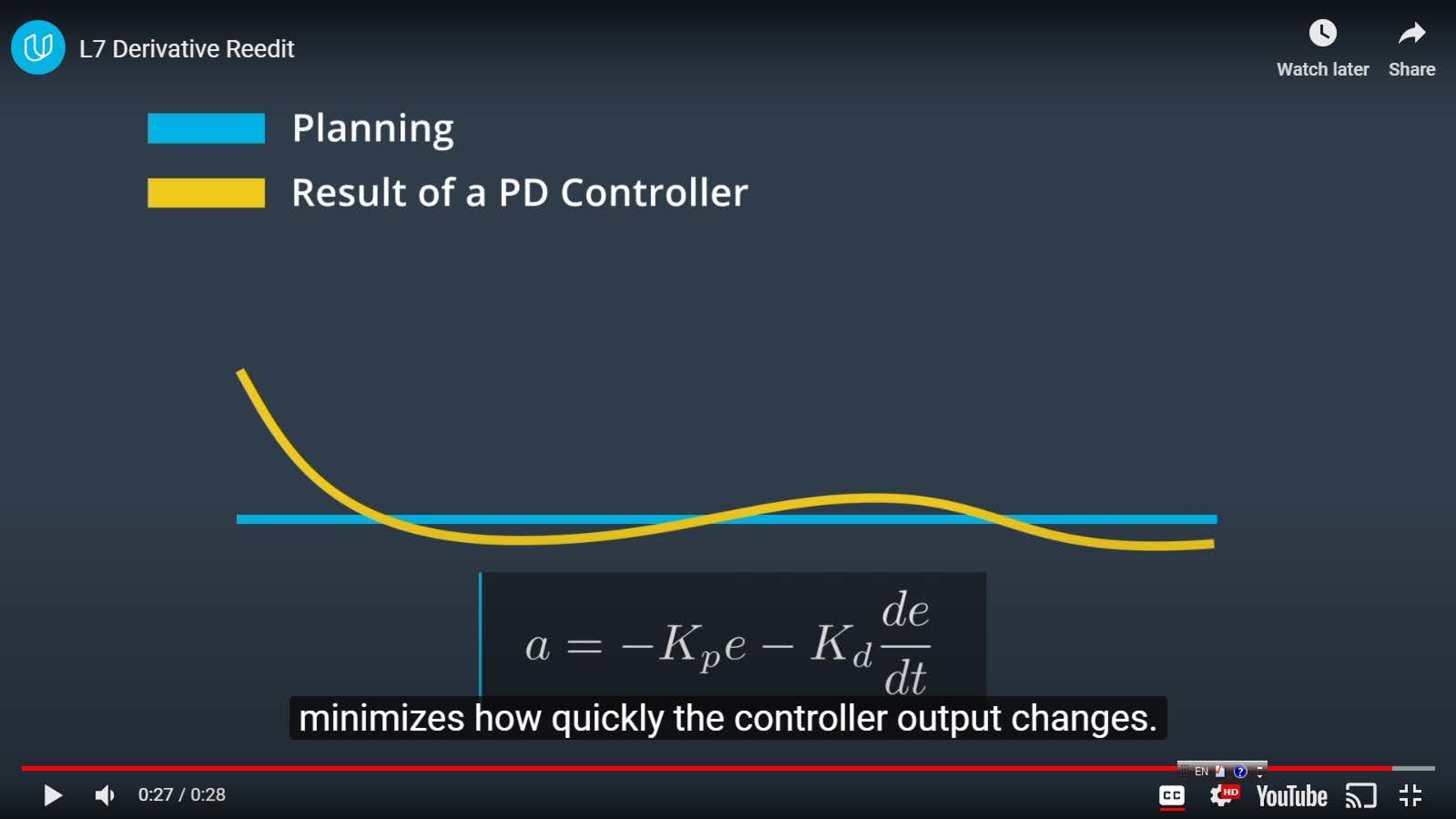


- A
- ✓ B
- C


Planning
Result of a P Controller
a P controller is that it's easy to overshoot the reference trajectory.
0:06 / 0:28

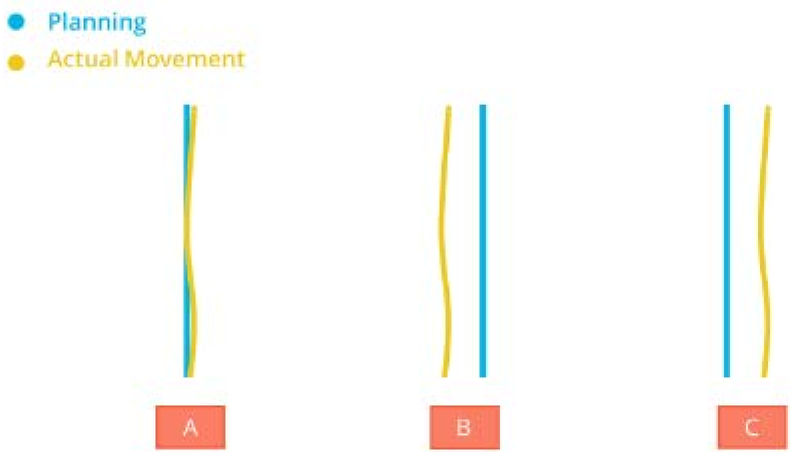

The D-term of the PID controller steadies its motion.
0:13 / 0:28
HD
YouTube


Planning
Result of a P Controller
D stands for derivative.
0:17 / 0:28
YouTube


L7 Derivative Reedit
Watch later
Share
Planning
Result of a PD Controller
$a = -K_p e - K_d \frac{de}{dt}$
minimizes how quickly the controller output changes.
0:27 / 0:28
YouTube

QUESTION 2 OF 2

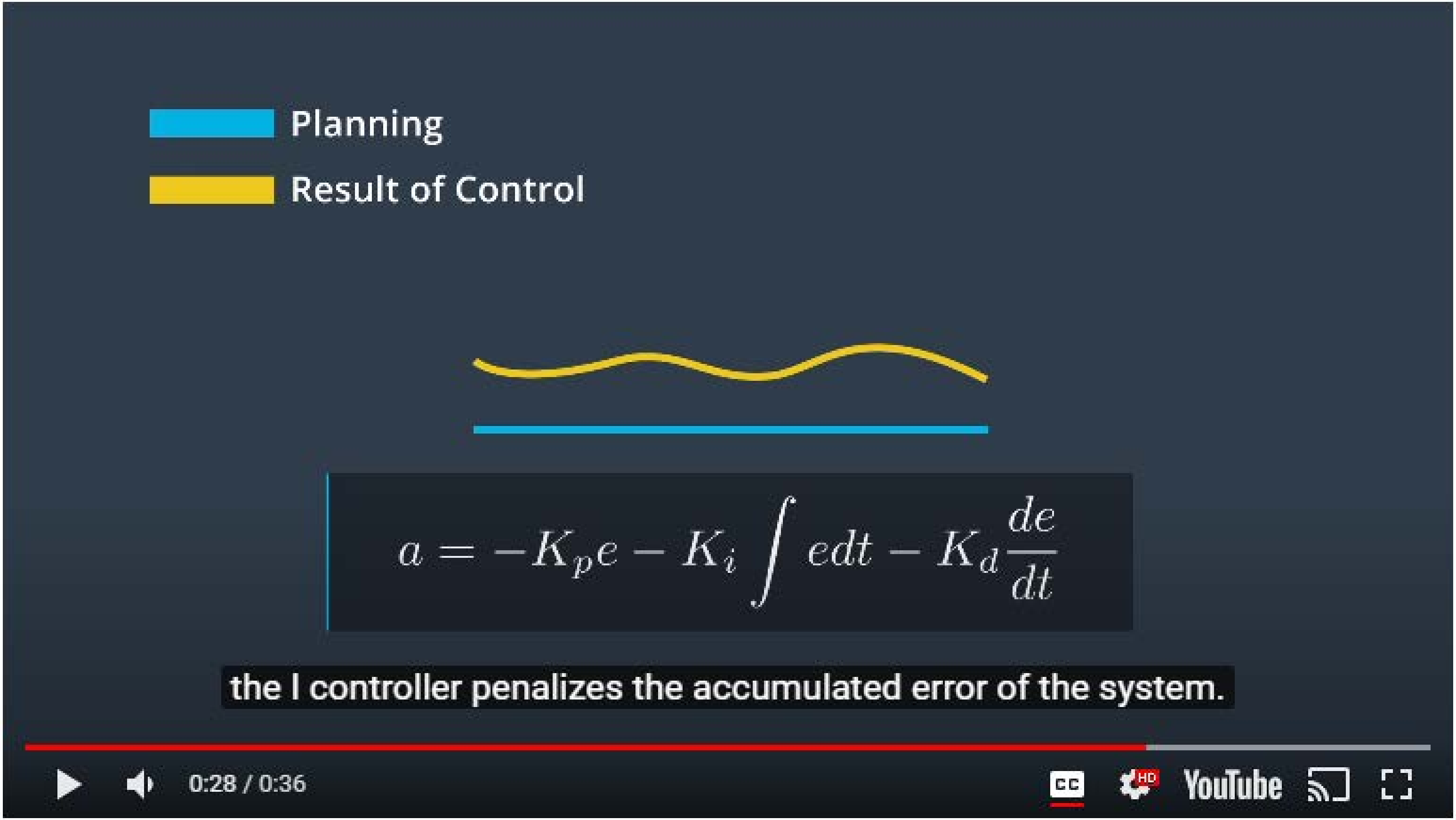
Suppose your steering system is drifted right, which means it produces extra angle to the right. If the drift is constant. What would happen when you apply a PD controller ?



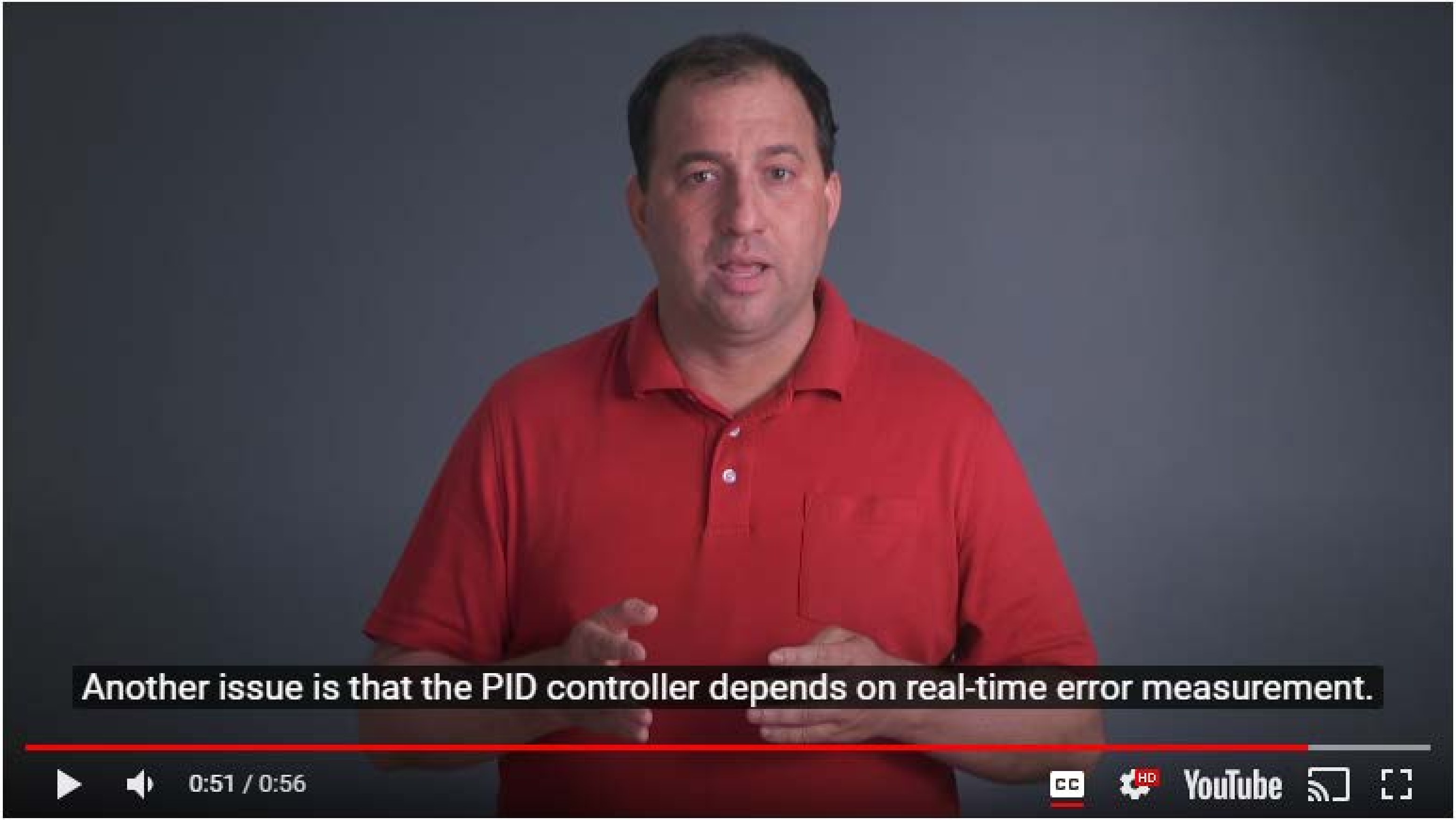
- A
- B
- C


The last component of a PID controller is the I or integral term.
0:05 / 0:36
HD
YouTube


This term is responsible for correcting any systemic bias of the vehicle.
0:10 / 0:36
HD
YouTube


Planning
Result of Control
$a = -K_p e - K_i \int e dt - K_d \frac{de}{dt}$
the I controller penalizes the accumulated error of the system.
0:28 / 0:36
YouTube


which means it's hard to combine a latitudinal and longitudinal control.
0:42 / 0:56
HD
YouTube


Another issue is that the PID controller depends on real-time error measurement.
0:51 / 0:56
HD
YouTube


That means it will probably fail when it subject to measurement delays.
0:53 / 0:56
HD
YouTube

PID Pros and Cons

Apollo provides two types of control strategy, one is the longitudinal and lateral decoupled control, the other is the MPC controller. In Apollo's control module, they rely on the longitudinal controller, the lateral controller, and the MPC controller.

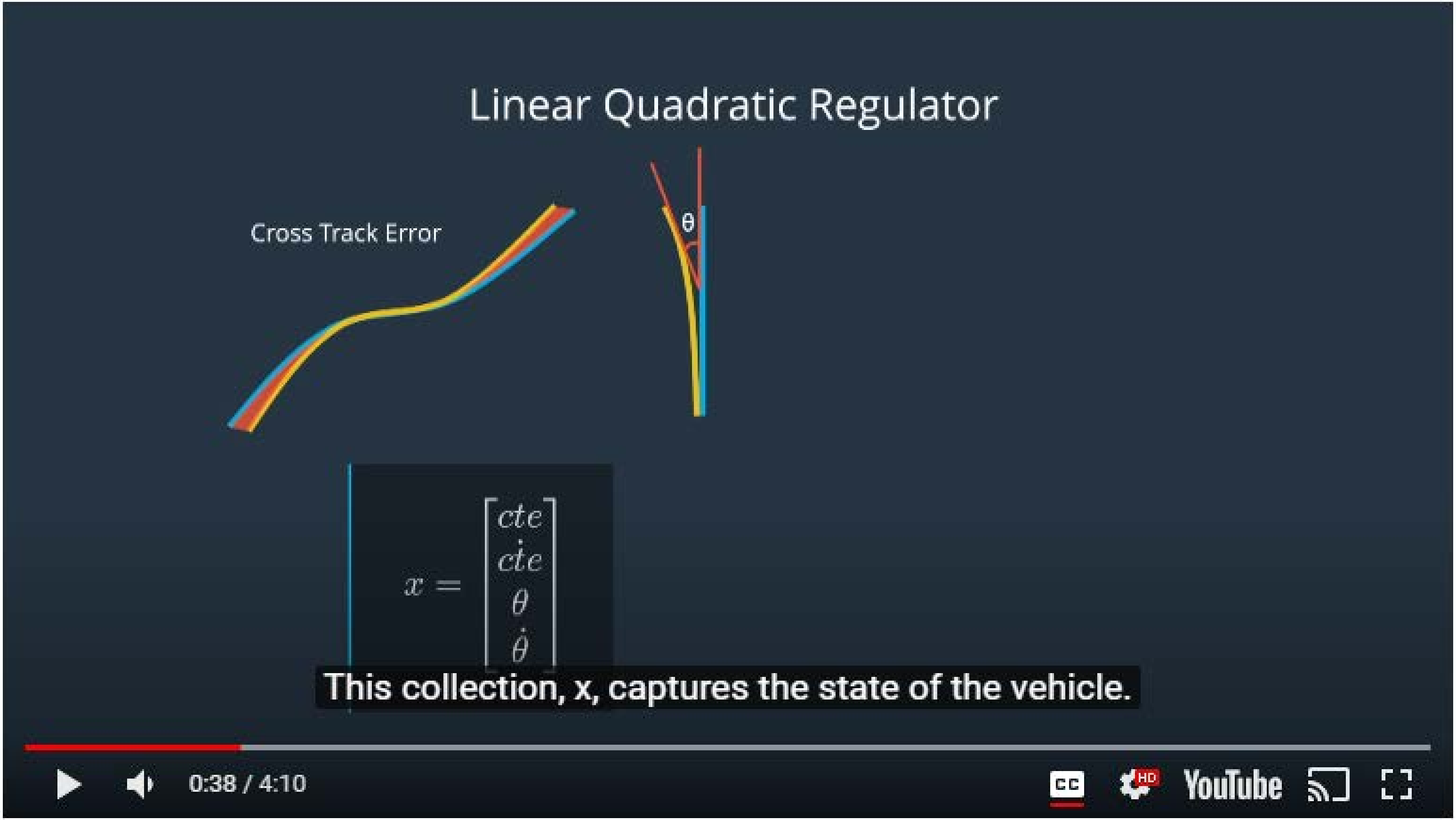
QUIZ QUESTION

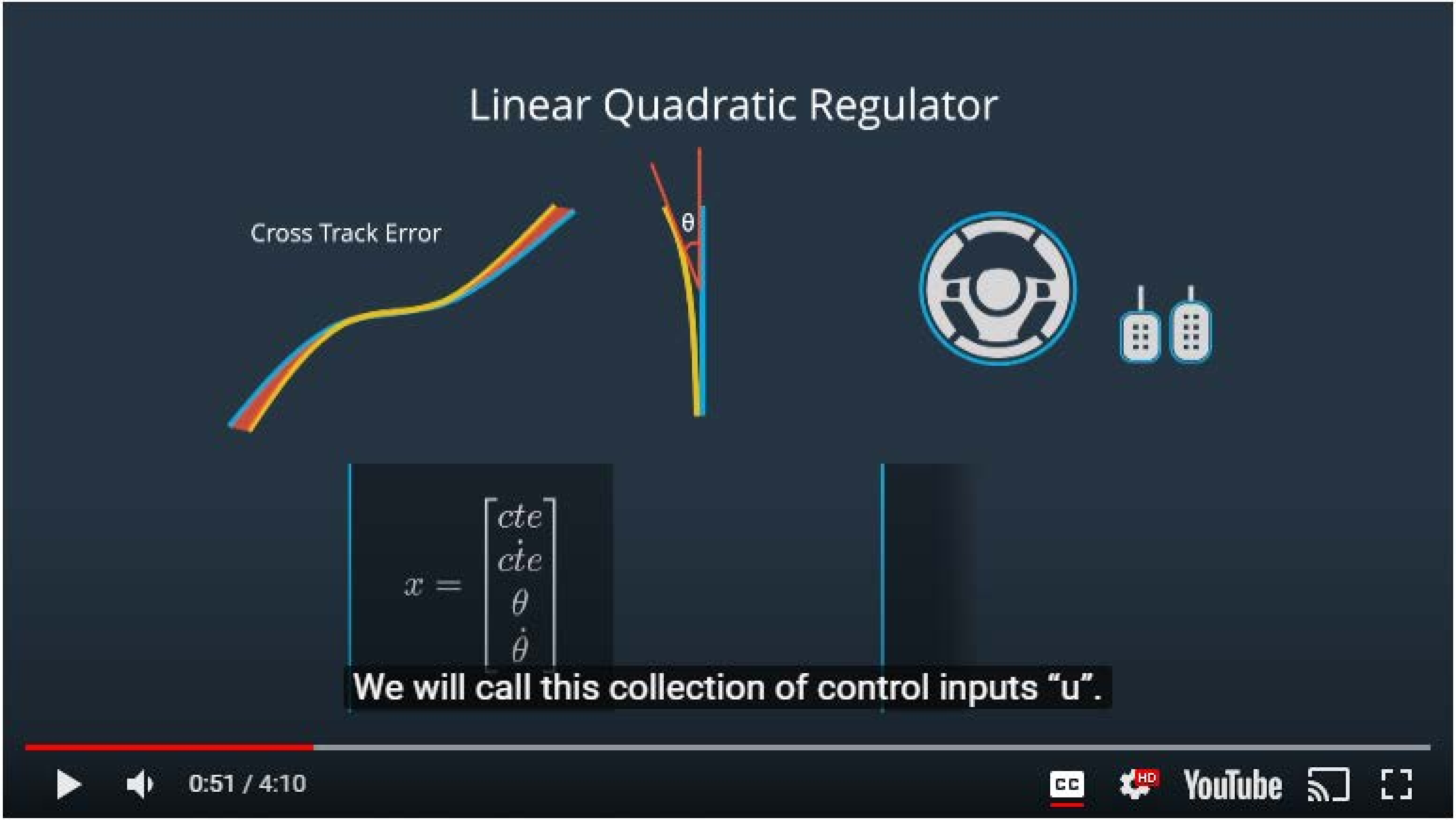
Take a look at the code of Apollo's control module, which of these three controllers are implemented using the PID control algorithm?

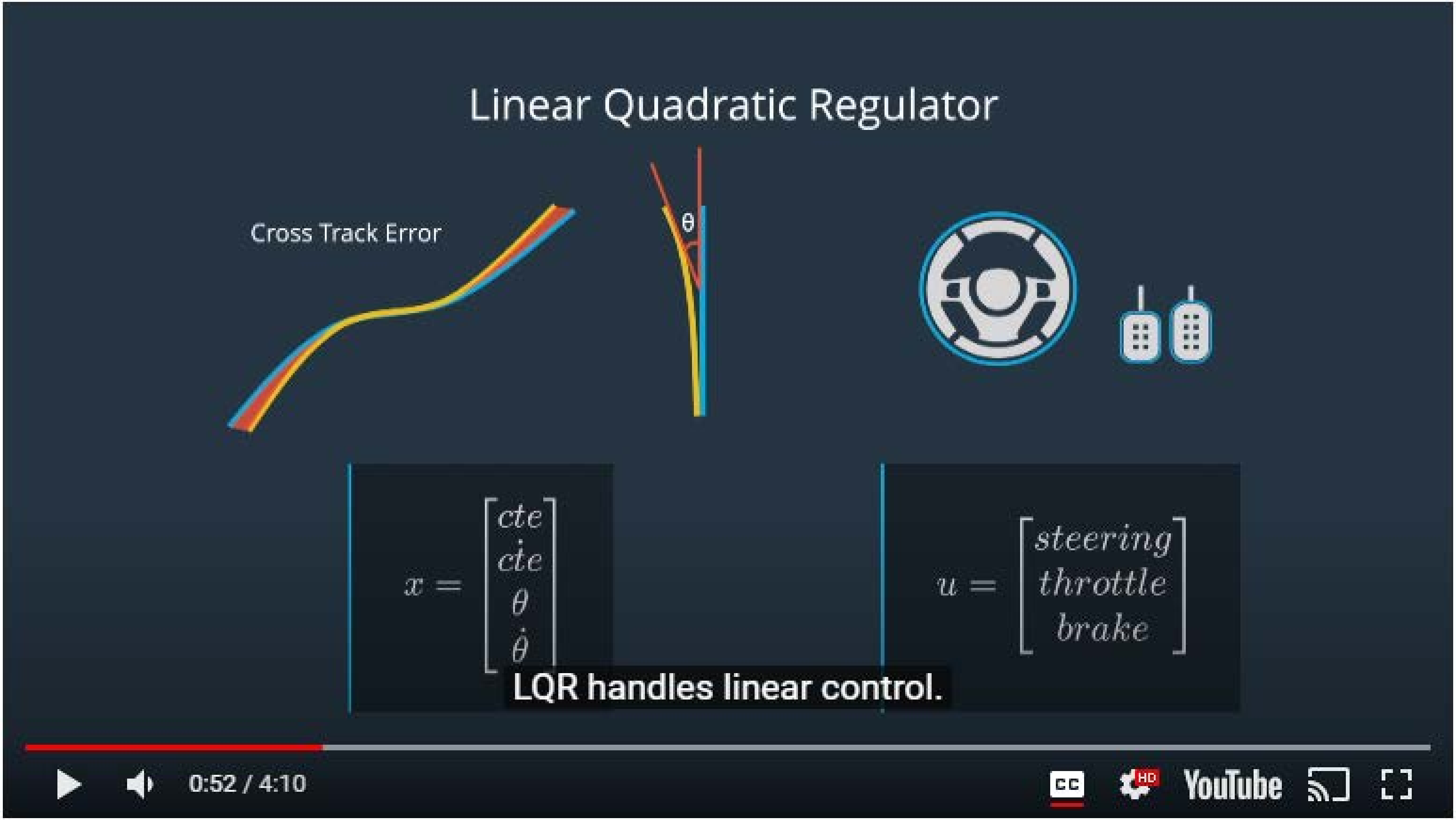
Hint: You can use browser search(`Cmd/Ctrl` + `F`*)*

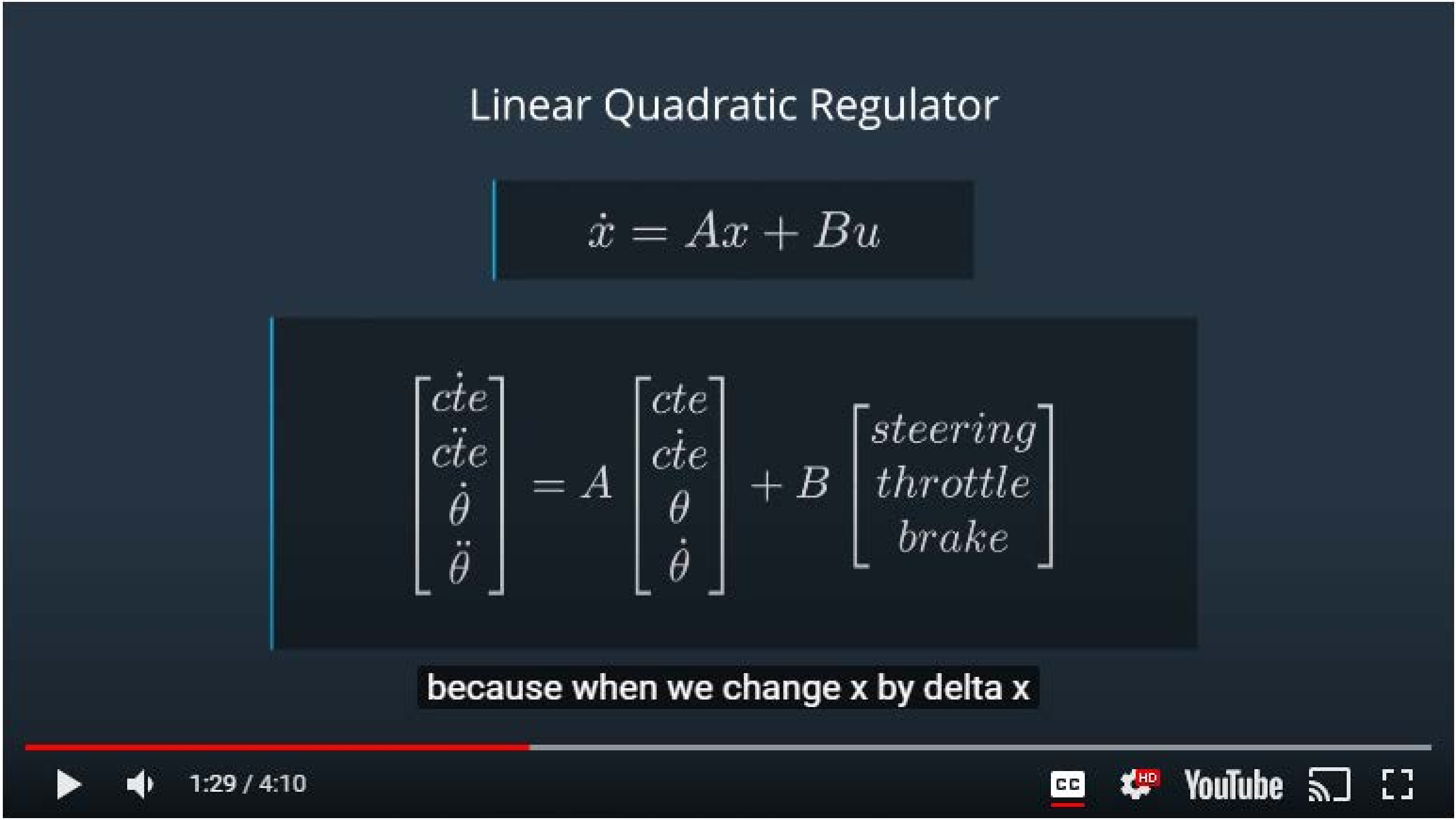
- [x] The Longitudinal Controller
- [ ] The Lateral Controller
- [ ] The MPC Controller


Apollo uses LQR for lateral control.
0:12 / 4:10
HD
YouTube


Linear Quadratic Regulator
Cross Track Error
θ
$x = \begin{bmatrix} cte \\ \dot{cte} \\ \theta \\ \dot{\theta} \end{bmatrix}$
This collection, x, captures the state of the vehicle.
0:38 / 4:10
HD
YouTube


Linear Quadratic Regulator
Cross Track Error
θ
$$x = \begin{bmatrix} cte \\ \dot{cte} \\ \theta \\ \dot{\theta} \end{bmatrix}$$
We will call this collection of control inputs "u".
0:51 / 4:10
YouTube

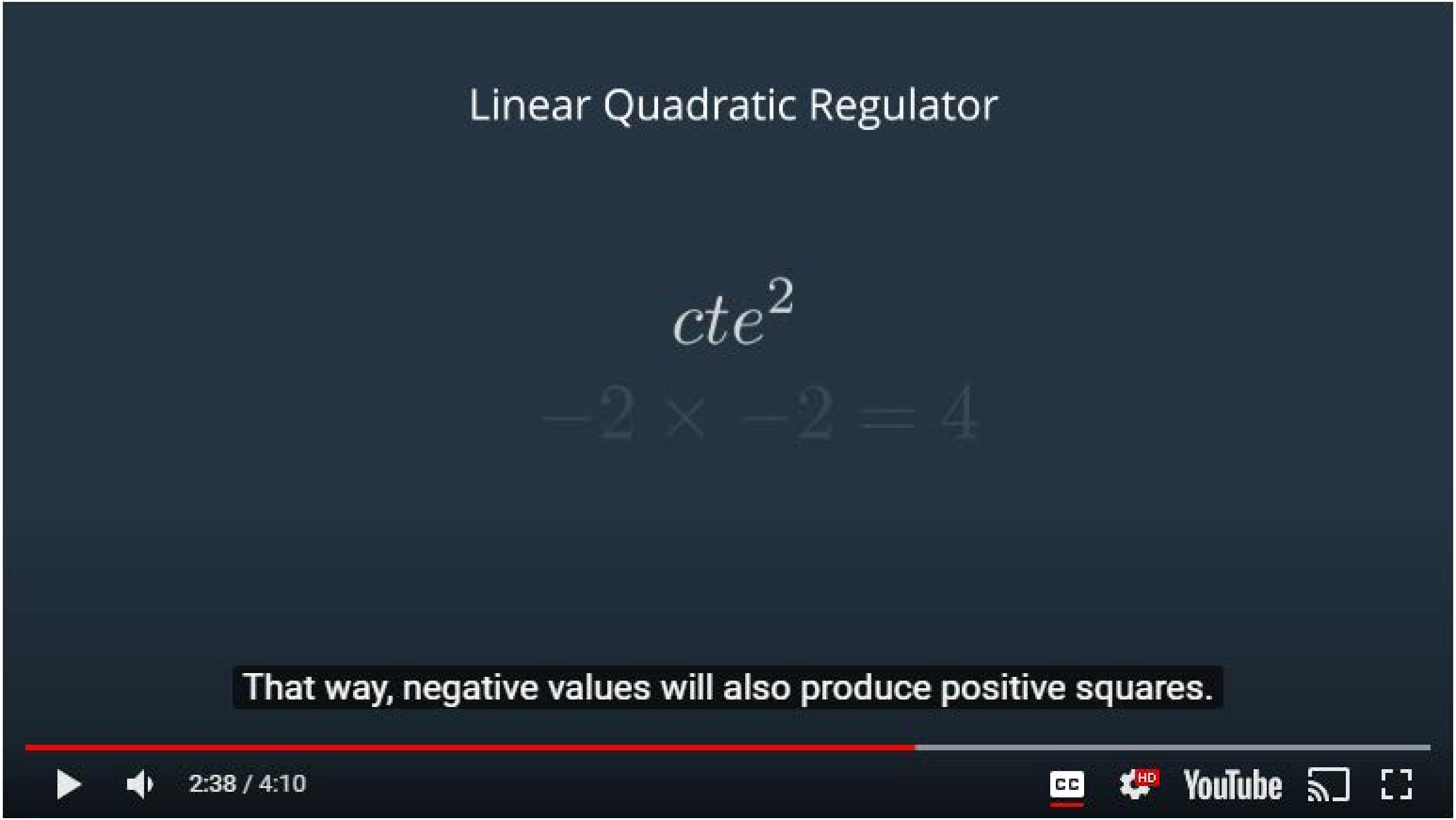

Linear Quadratic Regulator
Cross Track Error
θ
$x = \begin{bmatrix} cte \\ \dot{cte} \\ \theta \\ \dot{\theta} \end{bmatrix}$
$u = \begin{bmatrix} steering \\ throttle \\ brake \end{bmatrix}$
LQR handles linear control.
0:52 / 4:10
HD
YouTube

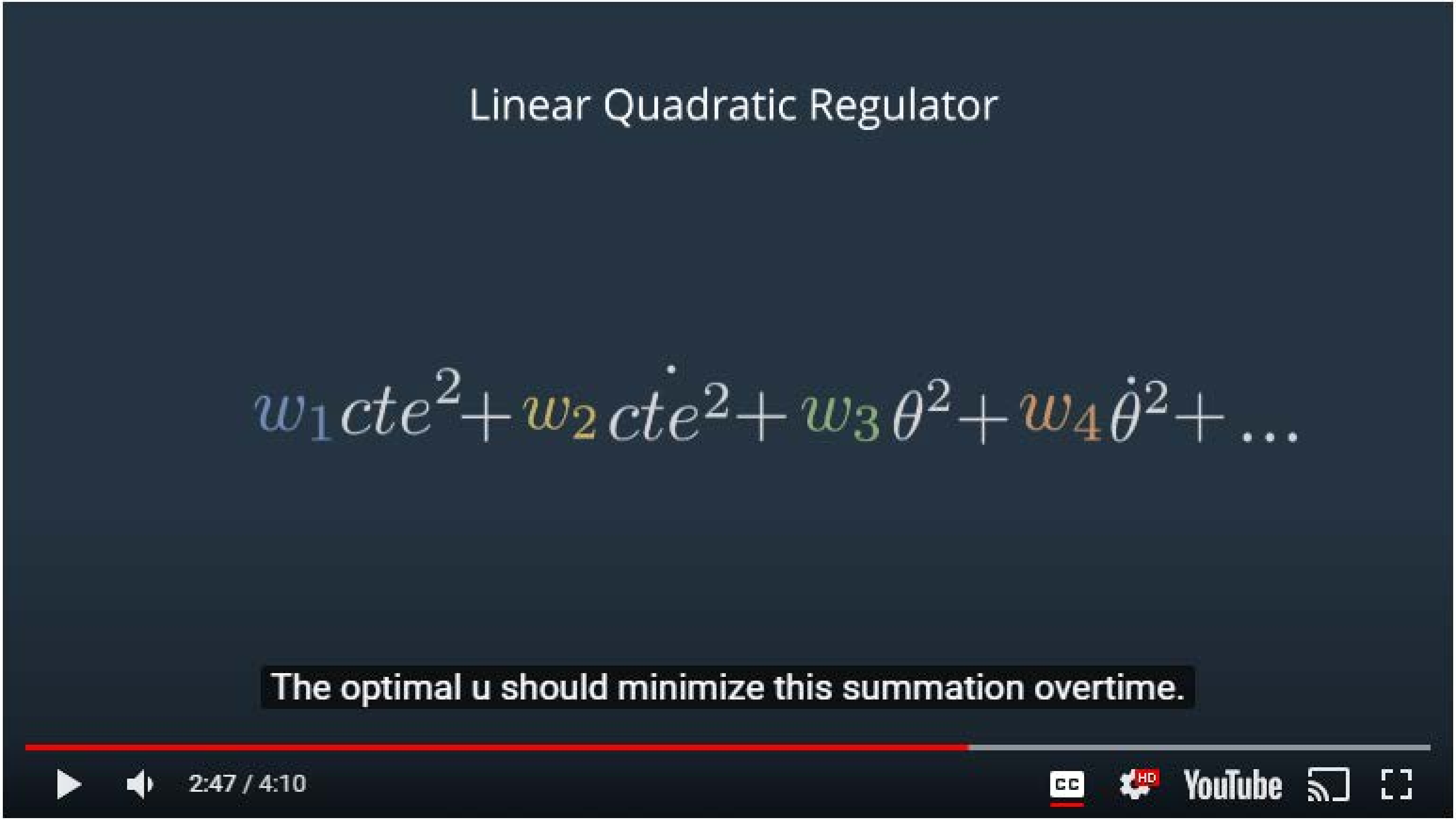

Linear Quadratic Regulator
$\dot{x} = Ax + Bu$
$\begin{bmatrix} \dot{cte} \\ \ddot{cte} \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = A \begin{bmatrix} cte \\ \dot{cte} \\ \theta \\ \dot{\theta} \end{bmatrix} + B \begin{bmatrix} steering \\ throttle \\ brake \end{bmatrix}$
because when we change x by delta x
1:29 / 4:10
YouTube

Linear Quadratic Regulator

$$\dot{x} + \Delta\dot{x} = A(x + \Delta x) + B(u + \Delta u)$$

$$\Delta\dot{x} = A\Delta x + B\Delta u$$


Linear Quadratic Regulator
cte^2
$-2 \times -2 = 4$
That way, negative values will also produce positive squares.
2:38 / 4:10
HD
YouTube


Linear Quadratic Regulator
$w_1 cte^2 + w_2 \dot{cte}^2 + w_3 \theta^2 + w_4 \dot{\theta}^2 + \ldots$
The optimal u should minimize this summation overtime.
2:47 / 4:10
HD
YouTube

Linear Quadratic Regulator

$$cost = \int_0^\infty (x^T \boxed{Q} x + u^T \boxed{R} u)dt$$

Here, Q and R represent a collection of weights for x and u.

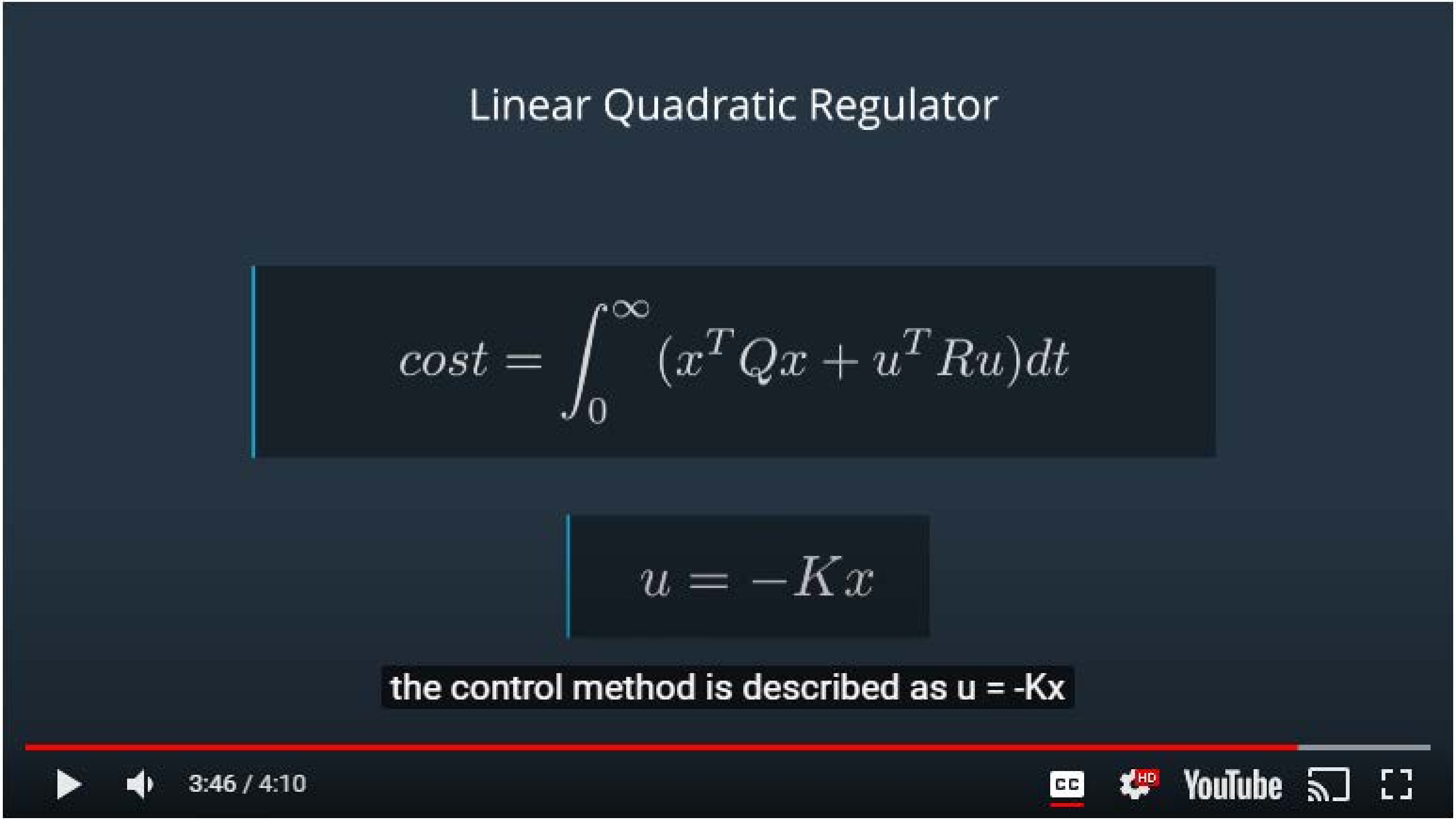
3:05 / 4:10

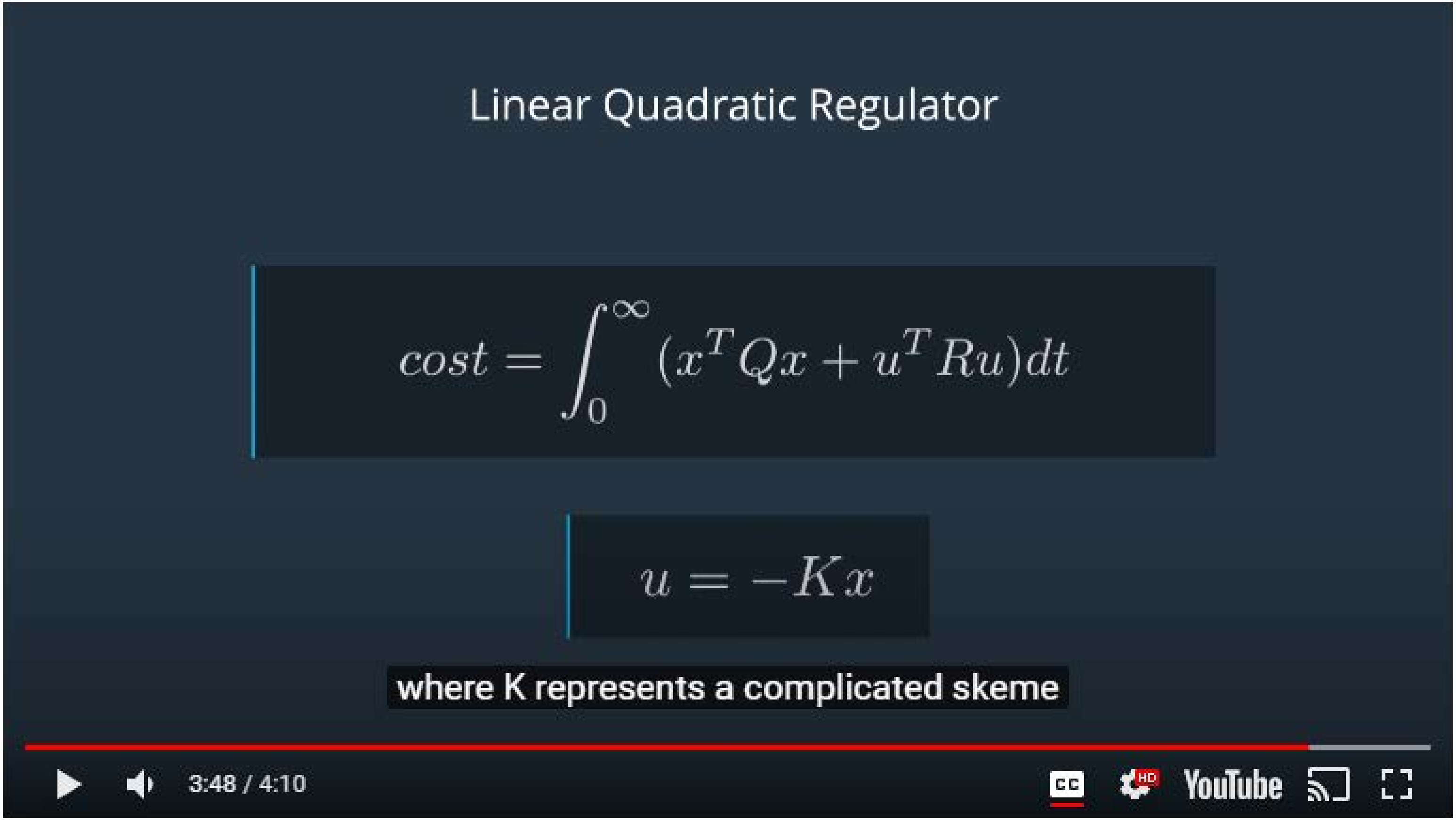
Linear Quadratic Regulator

$$cost = \int_0^\infty (\boxed{x^T} Qx + \boxed{u^T} Ru)dt$$

X-t and u-t are transpose matrices,

3:10 / 4:10


Linear Quadratic Regulator
$cost = \int_0^\infty (x^T Q x + u^T R u) dt$
$u = -Kx$
the control method is described as u = -Kx
3:46 / 4:10
YouTube


Linear Quadratic Regulator
$$cost = \int_0^\infty (x^T Q x + u^T R u) dt$$
$$u = -Kx$$
where K represents a complicated skeme
3:48 / 4:10

Linear Quadratic Regulator

$$cost = \int_0^\infty (x^T Q x + u^T R u)dt$$

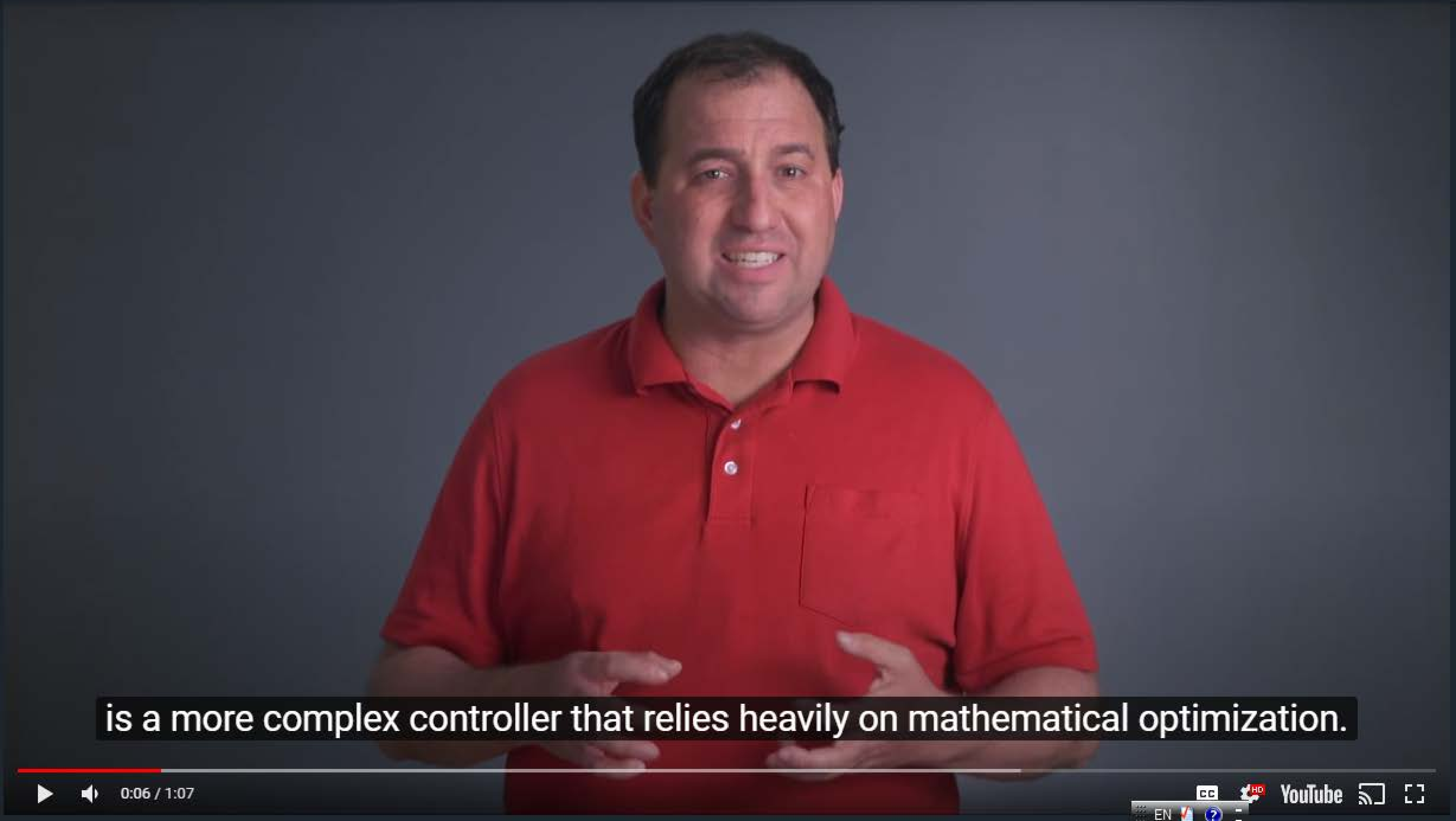
$$u = -\boxed{K}x$$

that indicate how to calculate u from x.

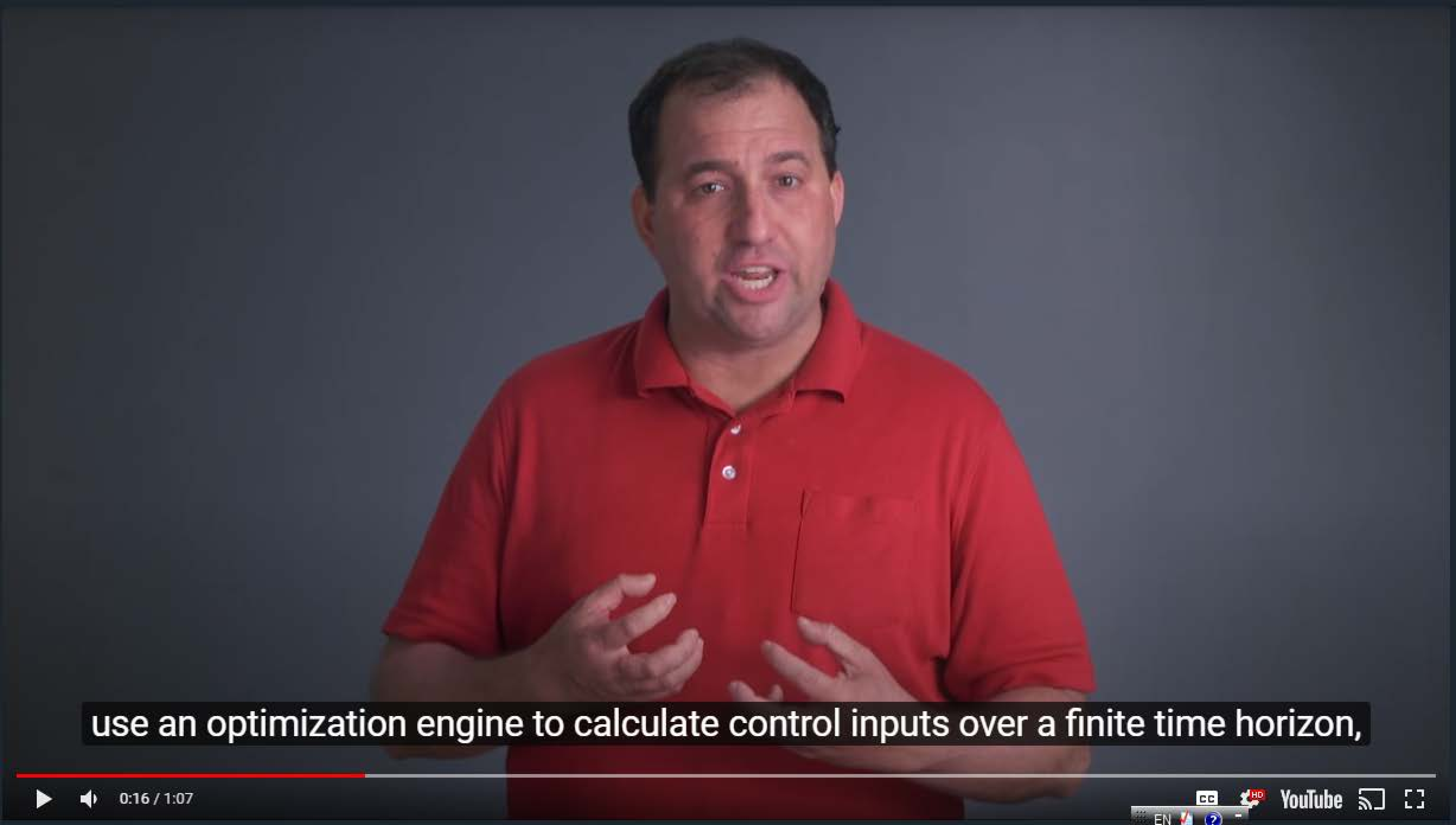
Correction : At 01:01, when David says Ax times Bu, it should be Ax plus Bu.

State-space Equation

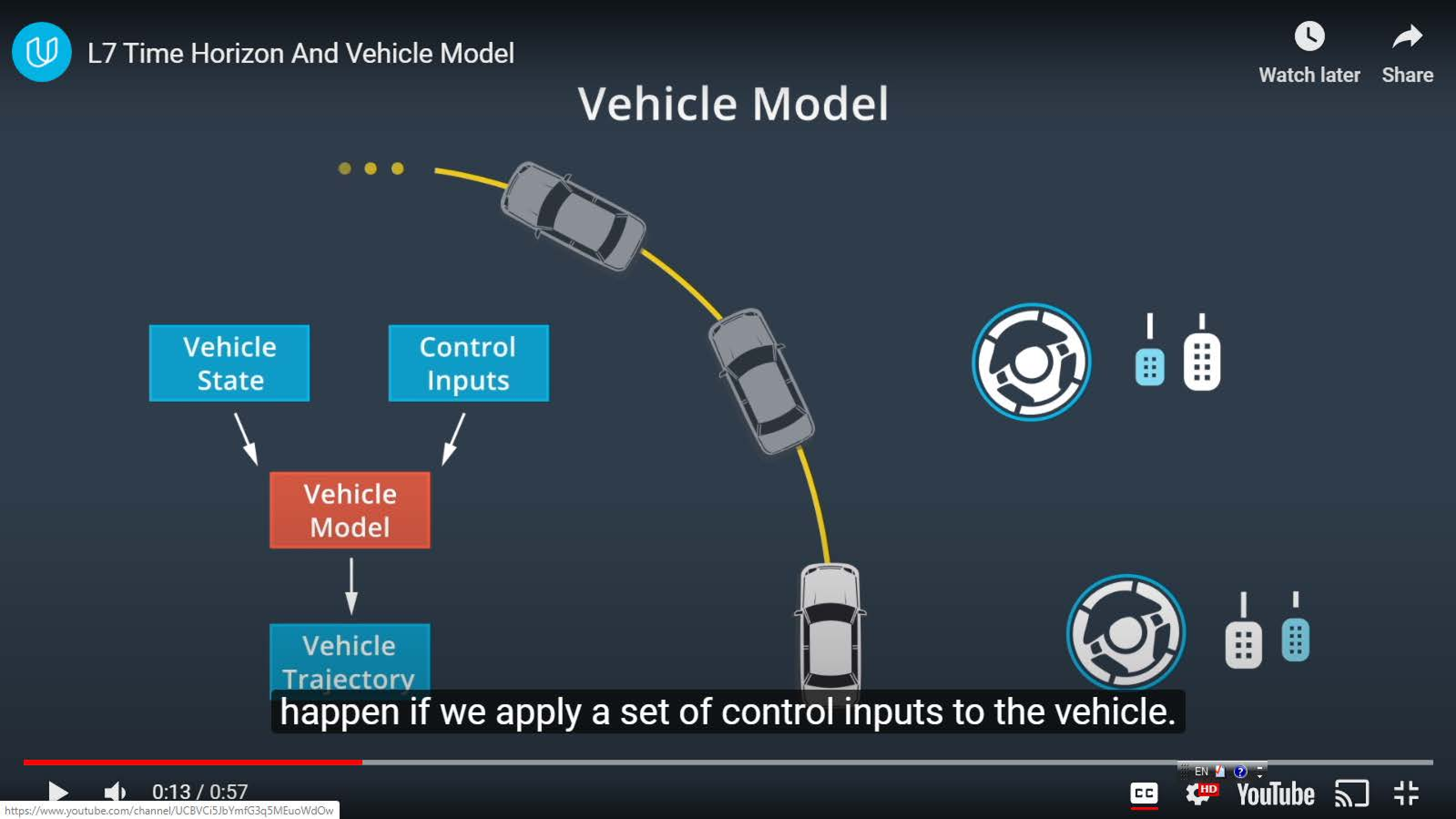
$\dot{x} = Ax + Bu$ is a State-space Equation, you can check out the subtopic, **Moving object example** in Wikipedia to see how it is derived from Newton's second law.


is a more complex controller that relies heavily on mathematical optimization.
0:06 / 1:07
YouTube

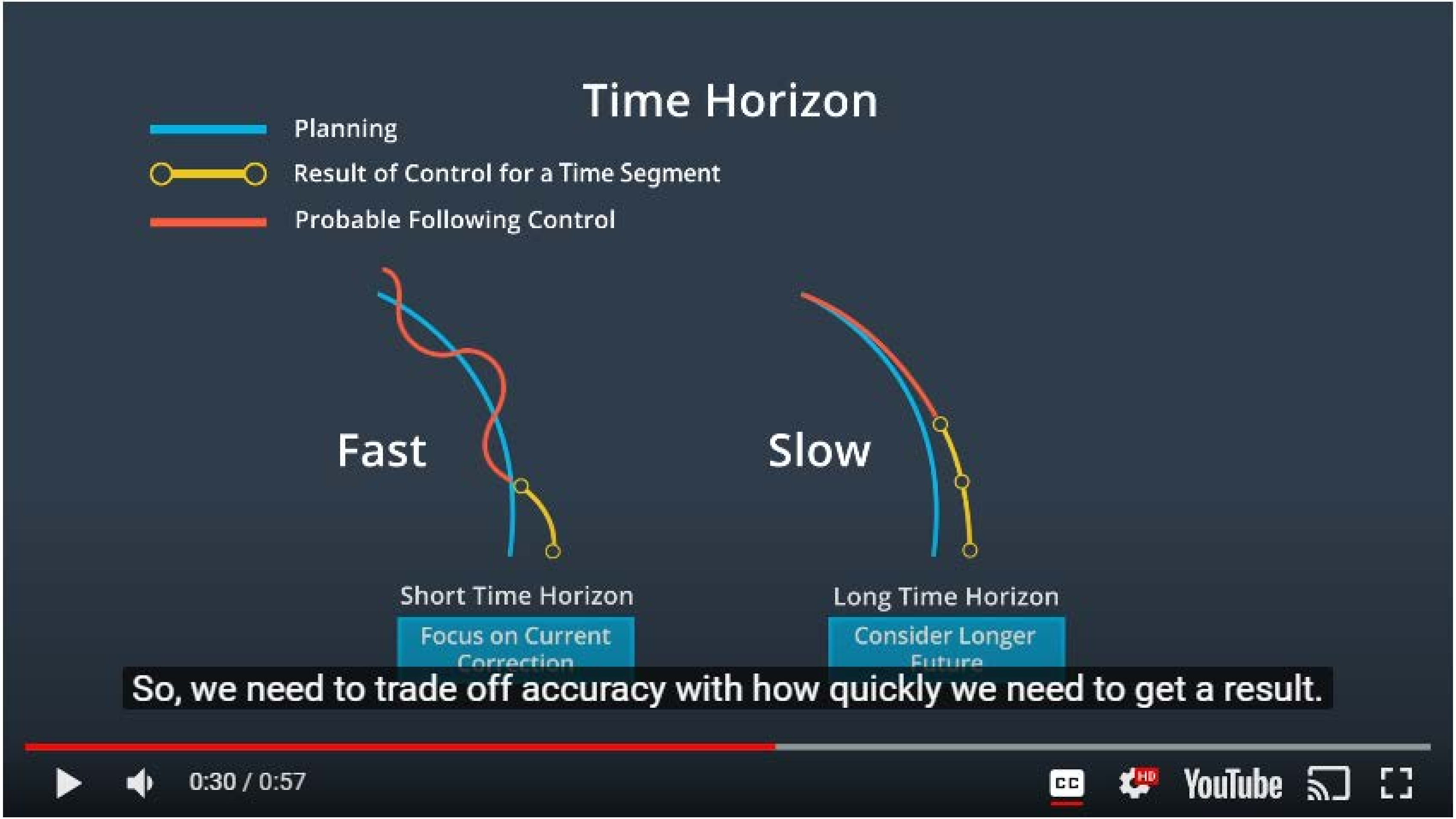

Build a model of the vehicle,
0:13 / 1:07
YouTube

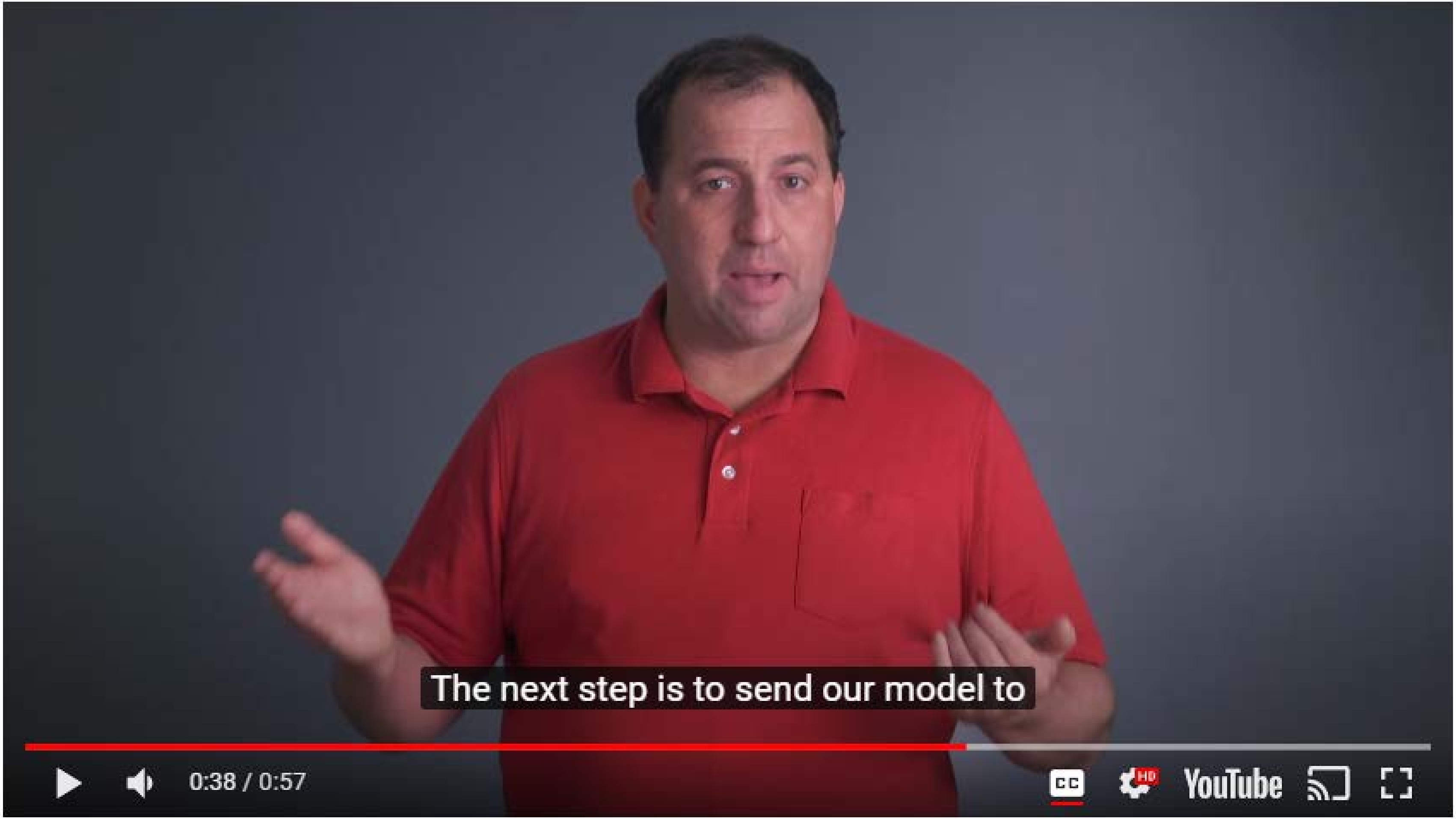

use an optimization engine to calculate control inputs over a finite time horizon,
0:16 / 1:07
YouTube


and then implement the first set of control inputs.
0:21 / 1:07
YouTube


L7 Time Horizon And Vehicle Model
Watch later
Share
Vehicle Model
Vehicle State
Control Inputs
Vehicle Model
Vehicle Trajectory
happen if we apply a set of control inputs to the vehicle.
0:13 / 0:57
https://www.youtube.com/channel/UCBVCi5JbYmfG3q5MEuoWdOw


Time Horizon
Next, we decide how far into the future we want MPC to look.
0:16 / 0:57
HD
YouTube


Time Horizon
Planning
Result of Control for a Time Segment
Probable Following Control
Fast
Slow
Short Time Horizon
Focus on Current Correction
Long Time Horizon
Consider Longer Future
So, we need to trade off accuracy with how quickly we need to get a result.
0:30 / 0:57


The next step is to send our model to
0:38 / 0:57
YouTube


an optimization engine that searches for the best control inputs.
0:40 / 0:57
YouTube

QUIZ QUESTION

The mechanism of the vehicle has certain constraints on its control, which means we cannot implement any control. Since our goal is to find a suitable control sequence, considering constraints can narrow the scope of our consideration and speed up the execution of the algorithm.

Which of the following are constraints of the vehicle?

- [x] Steering range that the vehicle can achieve
- [ ] Speed limit on the road
- [x] Acceleration range that can be used for acceleration/deceleration
- [ ] We need to drive within the legal region

Optimization for MPC
SEND FEEDBACK
Planning
Control Maneuvers
...
Discomfort
Jerking
Cross Track Error
Cost
and measures of passenger comfort.
0:22 / 0:52

MPC Pros and Cons

SEND FEEDBACK


It also works with different cost functions.
0:09 / 0:37
CC
HD
YouTube


On the other hand, Model Predictive Control is complex,
0:17 / 0:37
YouTube


slower, and harder to implement than PID control.
0:19 / 0:37
YouTube