Terrain-Adaptive Cruise Control; A Human-Like Approach

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TEXAS A&M UNIVERSITY

OUTLINE

- **Objectives**
- **Introduction**
  - Conventional Cruise Control System
  - Human Driving Behavior
  - Prevalent Approaches
- **Preliminaries**
  - Vehicle Model
  - Road Grade
- **Proposed Method**
  - Model
  - Objective Function
  - Control Algorithm
  - Simulation Results
- **Summary**

OBJECTIVES

- Design a speed control system that can:
  - *Track a set-speed along flat roads*
  - *Mimic human driving behavior along varying terrains*
- Ensure optimality of regulatory actions w.r.t (either or all),
  - *Fuel consumption,*
  - *Brake usage &*
  - *Acceleration.*

OBJECTIVES

- In a typical approach:
  - *Fixed-weight objective function is used*
  - *Pre-processing algorithms are needed*
  - *To ensure speed tracking*
  - *Fuel savings of 2.5% over 127km*
- In this approach:
  - *Varying-weight objective function is used*
  - *No need for pre-processing algorithms*
  - ***0.48%**(downhill) and **0.44%**(uphill) fuel savings over **2.5km***

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Conventional Speed Control

Aim	Maintain a user-set vehicle speed
Means	Controllers - PI, LQR, Fuzzy, ..., etc.
Actuators	Accelerator, Brakes
Sensors	Wheel Speed Sensor
Advantages	On flat roads:
	Robust tracking of set-speed
	Reduce driver fatigue
	Fuel efficient

Conventional Speed Control

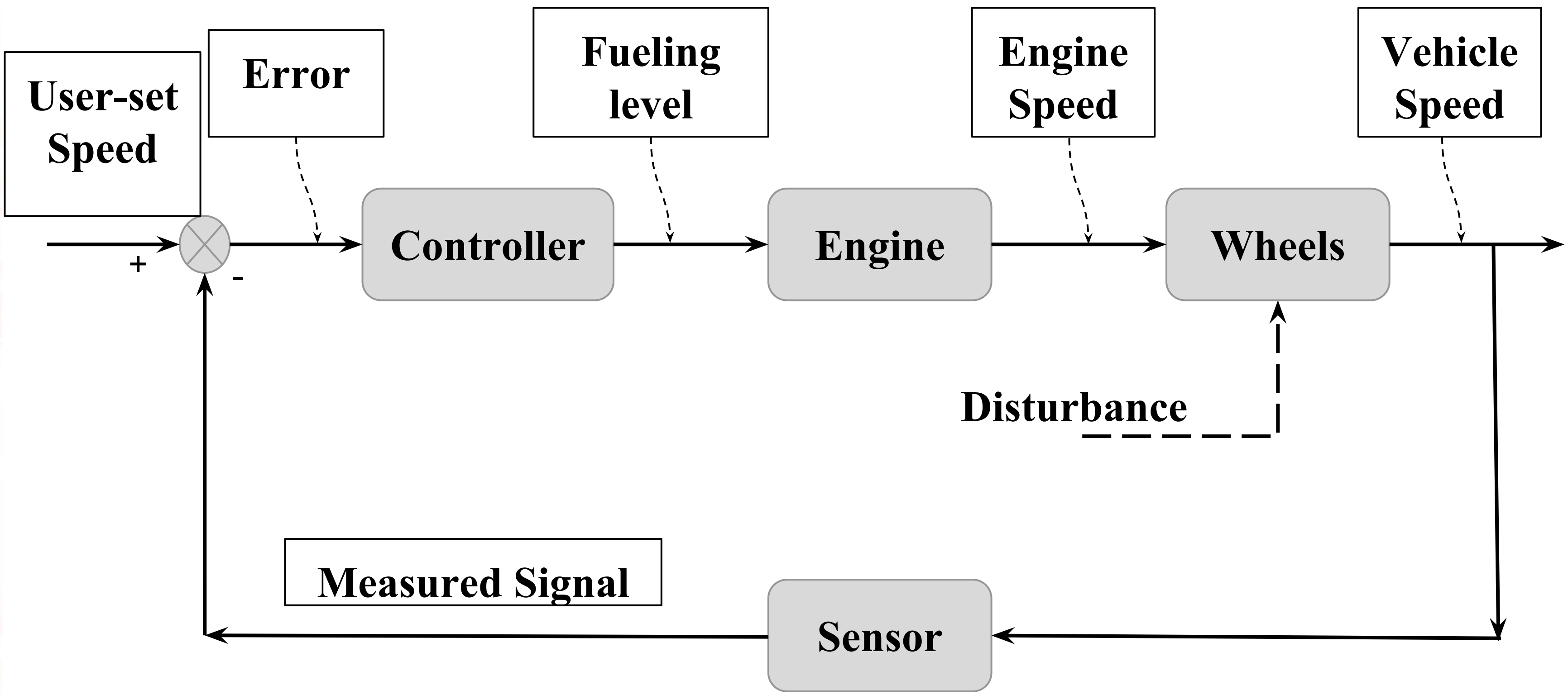

Figure 1: Block Diagram Of A Typical Conventional Speed Control System

Conventional Speed Control

Disadvantages

- *Oblivious to impending gradients*
  - Lot of energy is used up while going up a hill
  - Lot of energy is wasted while going down a hill
- *Unaware of curves along a route*
  - Set speed may not be safe along curvatures
  - Necessitates manual intervention
- *Always tries to maintain the highest possible gear*

Human Driving Behavior

- *Preview* Utilization
- *Accelerate* before and during an uphill
- *Decelerate* before a downhill
- *Coast* during descent
- Right choice of *gear*

Unfamiliar route, novice driver, bad driving practices?

Prevalent Approaches

1. Heuristic Algorithm[1]
   a. Road section is divided based on the terrain - *uphill, downhill and flat*
   b. Intuitive rules mapping inputs to the outputs are generated
   c. Computationally less intense
   d. Generation of rule base is tedious

[1] Mustafa Abdul Rasool, Master's Thesis in Automatic Control, KTH.

Prevalent Approaches

2. Model Predictive Control Scheme
   a. Constrained optimization with gradient descent algorithm[2]
      i. Local minimum
      ii. Optimal velocity trajectory
      iii. Linear controller with gain scheduling
   b. Discrete Dynamic Programming[3]
      i. Fixed objective function
      ii. State-space & Input-space are discretized
      iii. Pre-processing algorithm is needed

[2] US 6990401 B2, Daimler Chrysler Ag, [3] Erik Hellstrom, Maria Ivarsson, Jan Aslund, Lars Nielsen, Linkoping University.

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Vehicle Model

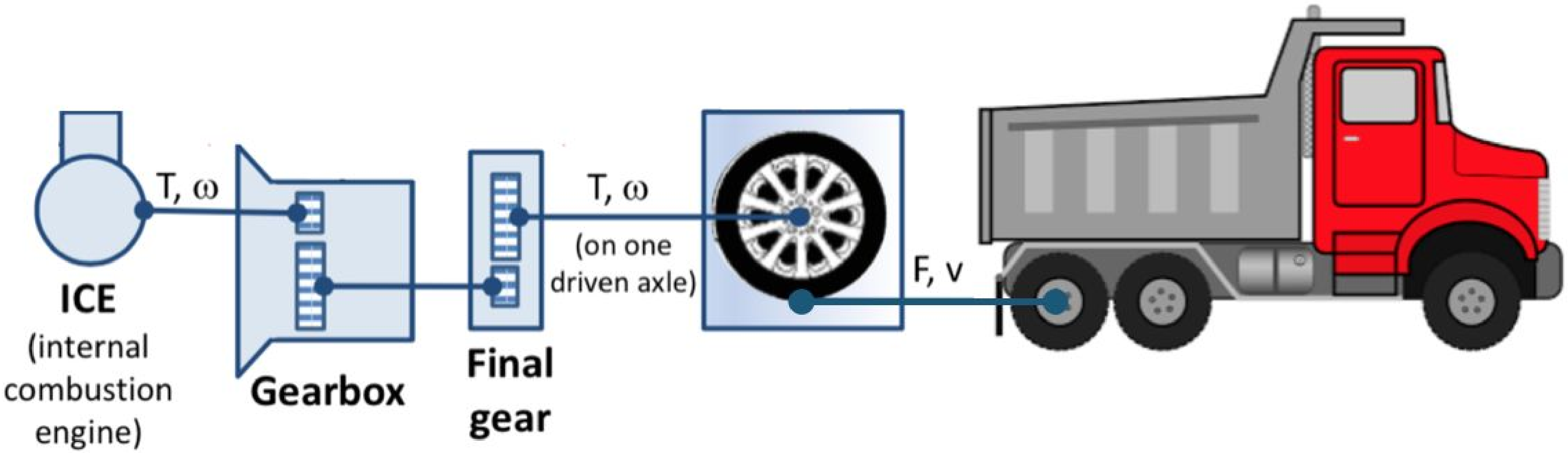
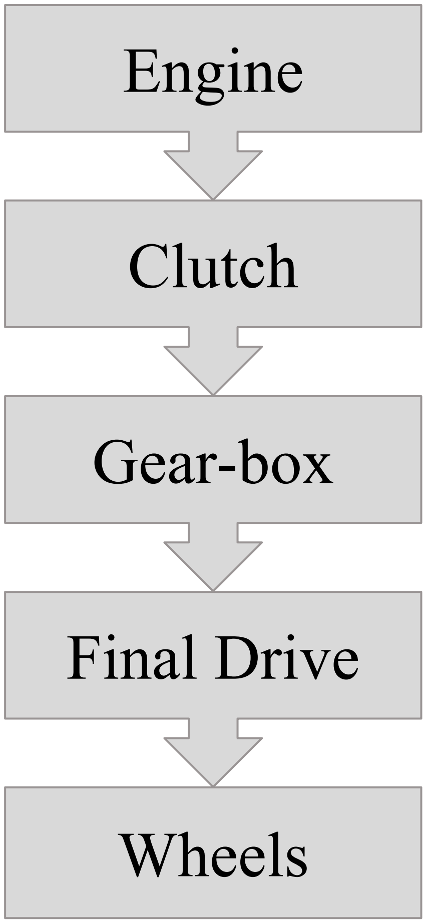


Figure 3: A Typical Automotive Power-train[4]

[4] Jacobson, B. (2012), Chalmers University of Technology.

Vehicle Model



$$T_e(P,N,G) = \begin{cases} a_e N + b_e P \delta_{max}(N) + c_e, & P > 0, G \neq 0 \\ a_d N + b_d, & P \leq 0, G \neq 0 \\ 0, & G = 0 \end{cases}$$

$$T_c = T_e$$

$$T_t = \eta_t i_t T_c$$

$$T_f = \eta_f i_f T_t$$

$$T_w = T_f$$

Parameter	**Description**
T	Torque Output (*N-m*)
P	Accelerator Pedal
G	Gear Position
N	Engine Speed (*RPM*)
a, b, c	Empirical Constants
i	Conversion Ratio
η	Efficiency (*%*)

Vehicle Model

Air Drag → $$F_d = \frac{1}{2}\rho c_d A v^2$$

Rolling Resistance → $$F_r = mgc_r cos(\alpha)$$

Gradient Resistance → $$F_g = mgsin(\alpha)$$

Parameter	**Description**
c	Friction Coefficient
m	Mass (kg)
A	Frontal Area ($sq.\ m$)
v	Velocity (m/s)
g	Acceleration due to gravity (m/s^2)
ρ	Density of air (kg/m^3)
α	Road Grade ($rads$)

$$F_{total} = F_d + F_r + F_g$$

Vehicle Model

Tractive Force at the wheels

$$T_w = F_w r_w$$

$$F_w = F_e - F_{total}$$

Parameter	Description
F	Tractive Force (kN)
J	Inertia (kg/m^2)
r_w	Wheel Radius (m)

$$\dot{v} = \frac{r_w}{J_w + mr_w^2 + \eta_t i_t^2 \eta_f i_f^2 J_e}(\eta_t i_t \eta_f i_f T_e(N,P,G) - BF_B - 0.5\rho c_d r_w A v^2 - mgr_w\sqrt{1+c_r^2}sin(\alpha + \arctan(c_r)))$$

Road Grade (α)

$$\alpha(rads) = \frac{Vertical\ Projection}{Horizontal\ Projection}$$

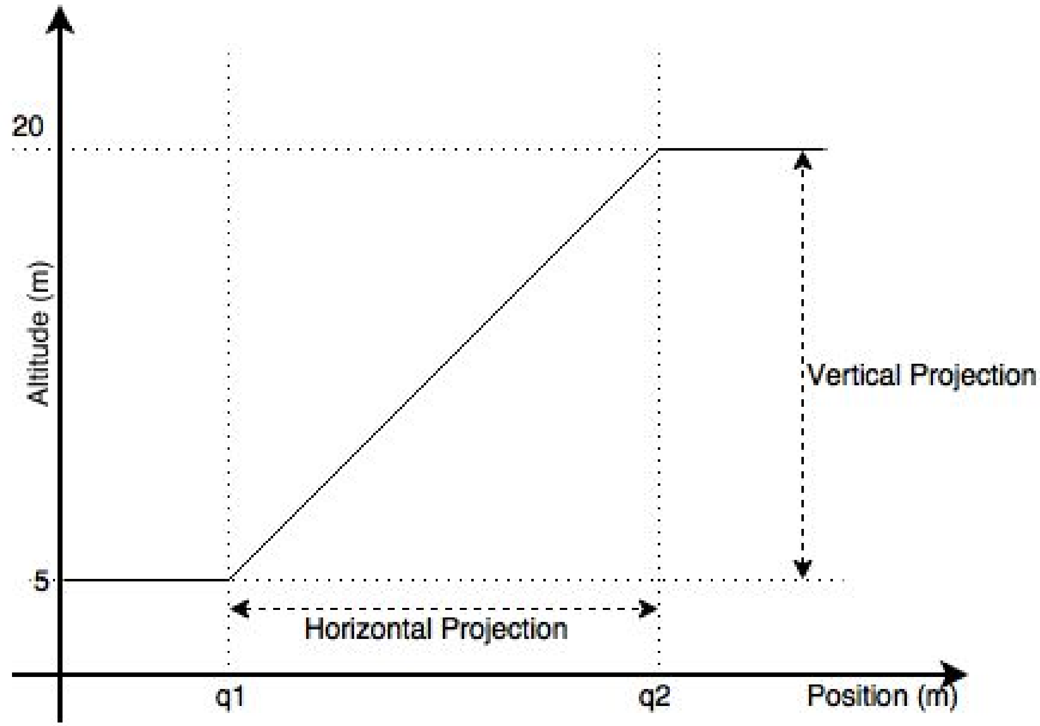


Figure 4: Pictorial Representation Of Road Grade

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Overview

1. Discretize the vehicle model
   a. Define States, Inputs & Outputs
   b. Define Constraints
2. Formulate an objective function
   a. Adaptively vary the weights
3. Implement a MPC scheme with discrete dynamic programming
   a. Apply the first instance of the control action
   b. Measure the output
   c. Recompute the control action

Model

State: $$v_{k+1} = v_k + \frac{h}{v_k} f_1(v_k, u_k, \alpha_k),\ k = 0, 1, 2, \ldots, N-1$$

Inputs: $$u_k = \begin{bmatrix} P_k \\ B_k \end{bmatrix},\ k = 0, 1, 2, \ldots, N-1$$

Outputs: $$y_k = \begin{bmatrix} v_k \\ m_{f,k} \end{bmatrix},\ k = 0, 1, 2, \ldots, N-1$$

Constraints: $$(v_{ref} - 5) \leq v_k \leq (v_{ref} + 5)$$

$$0 \leq P_k \leq 1$$

$$0 \leq B_k \leq 1$$

Objective Function

Cost Criteria: B_k, Brake usage

$m_{f,k}$, Fuel usage

$|v_k - v_{k+1}|$, Acceleration

$|v_{ref} - v_k|$, Deviation in velocity

Objective Function:

$$\beta_k = L_1(\alpha_k) m_{f,k} + L_2(\alpha_k)|v_{ref} - v_k| + L_3(\alpha_k)|v_k - v_{k+1}| + L_4(\alpha_k) B_k$$

$L_1(\alpha_k),\ L_2(\alpha_k),\ L_3(\alpha_k)$ & $L_4(\alpha_k)$ are *terrain dependent* penalties.

Terrain Dependent Objectives

- Flat Stretch (F):
  - Track Set-Speed
- Uphill (U):
  - Accelerate Before Ascent
  - Accelerate Upon Ascent
  - Reduced Speed Drop
- Downhill (D):
  - Decelerate Before Descent
  - Coast during descent
  - Minimal Brake Usage
  - Fuel Efficient

Gain	F	U	D
L_1	Low	Low	High
L_2	High	Low	Low
L_3	High	High	High
L_4	Low	Nil	High

Discrete Dynamic Programming

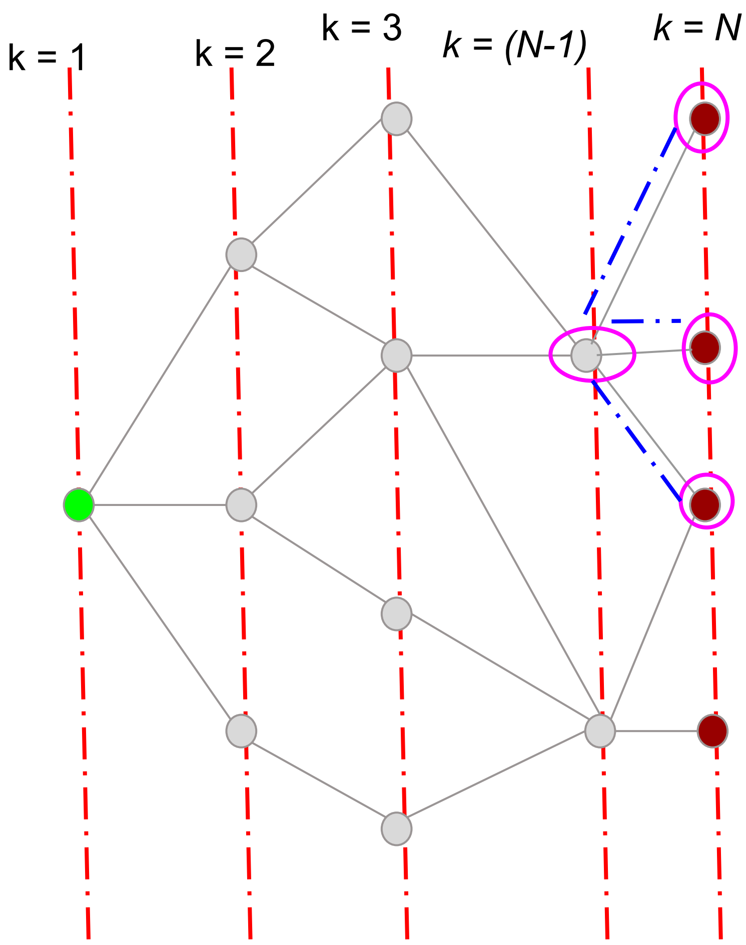


Figure 5: N-step Dynamic Programming Problem

1. At $k = N$,

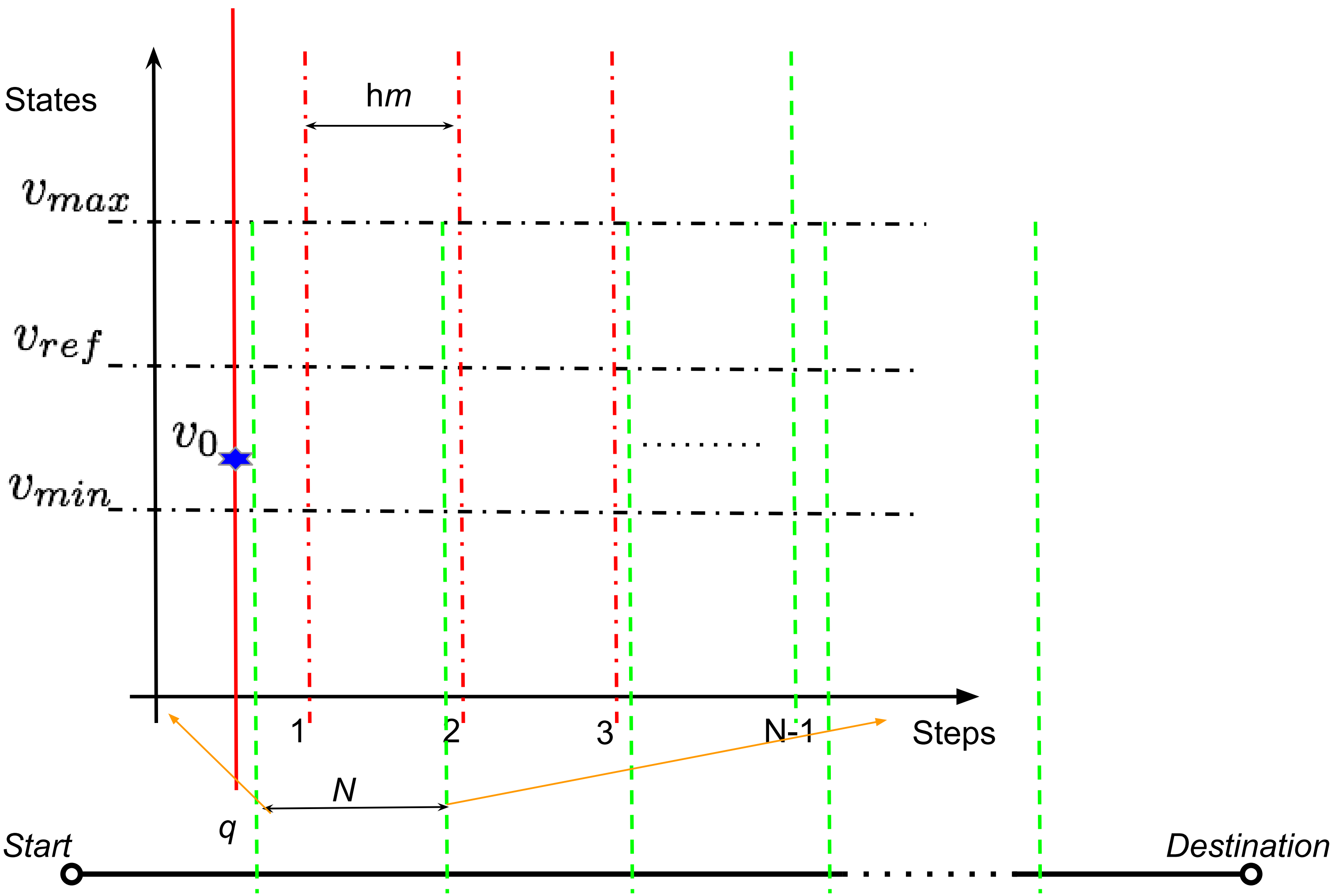
$$J_N(v_N(i)) = \beta_N(v_N(i)) = 0$$

2. Take a step backward, k = N-1,

$$J_k(v_k(i)) = \min_{v_{k+1}(j)} \{J_{k+1}(v_{k+1}(j)) + \beta_k^{i,j}\}$$

3. If $k>1$, repeat step 2

Model Predictive Control



Simulation

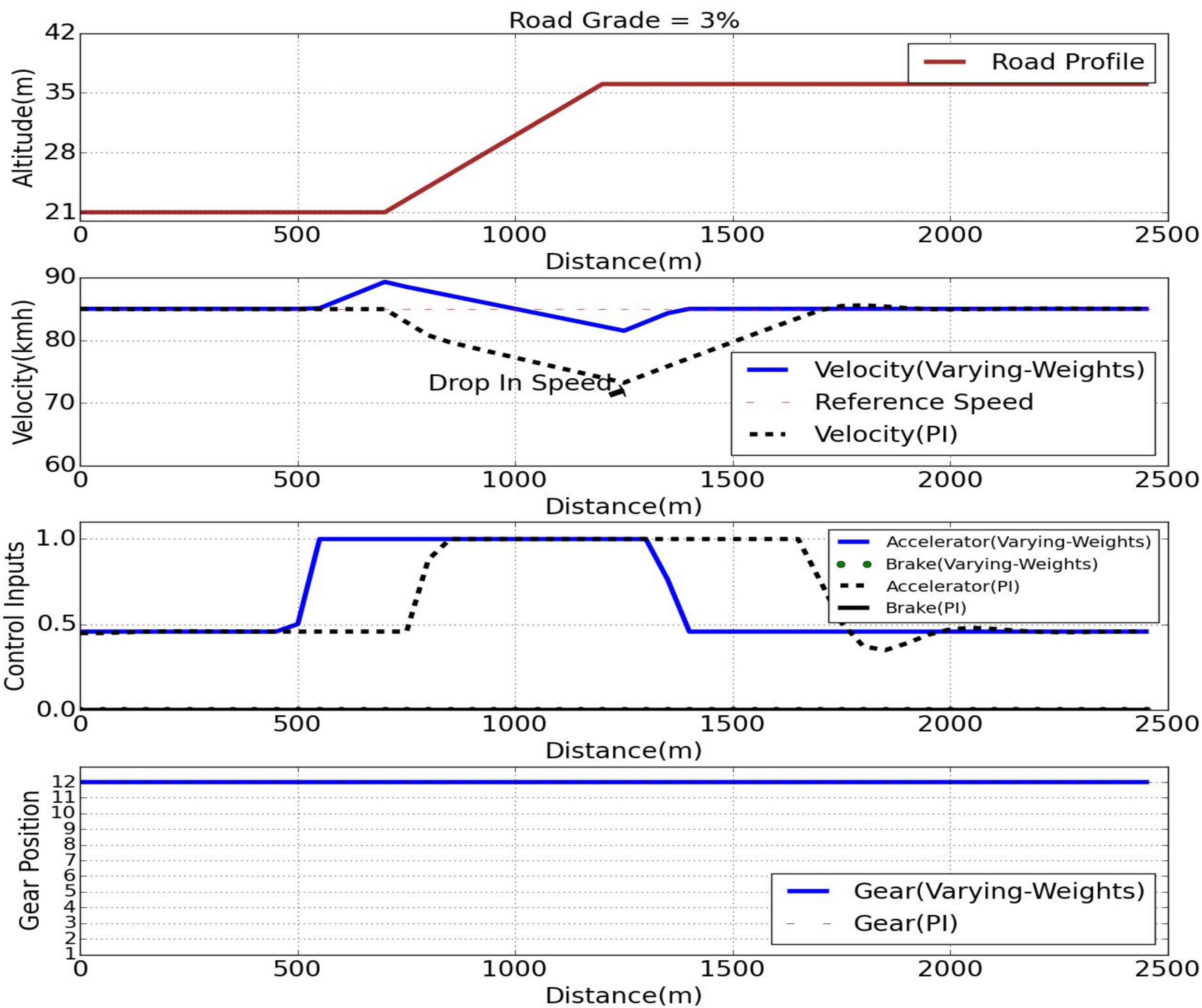
- Controllers (Julia):
  - PI Controller
  - Optimal Controller with fixed-weights
  - Optimal Controller with varying-weights
- Scenarios:
  - Uphill
  - Downhill

Artificial road sections of length 2500m with 500m of varying grade (uphill/downhill)

Simulation Parameters

Parameter	Description	Value
h	Step length	50m
N	No. Of Steps	30
v_{ref}	Reference Velocity	85 km/h
v_{min}	Lower Bound	80 km/h
v_{max}	Upper Bound	90 km/h
α	Road Grade	$\pm 3\%$

Performance Analyses Of PI Vs Varying-Weights Optimal Control (Fuel Savings = -0.44%)



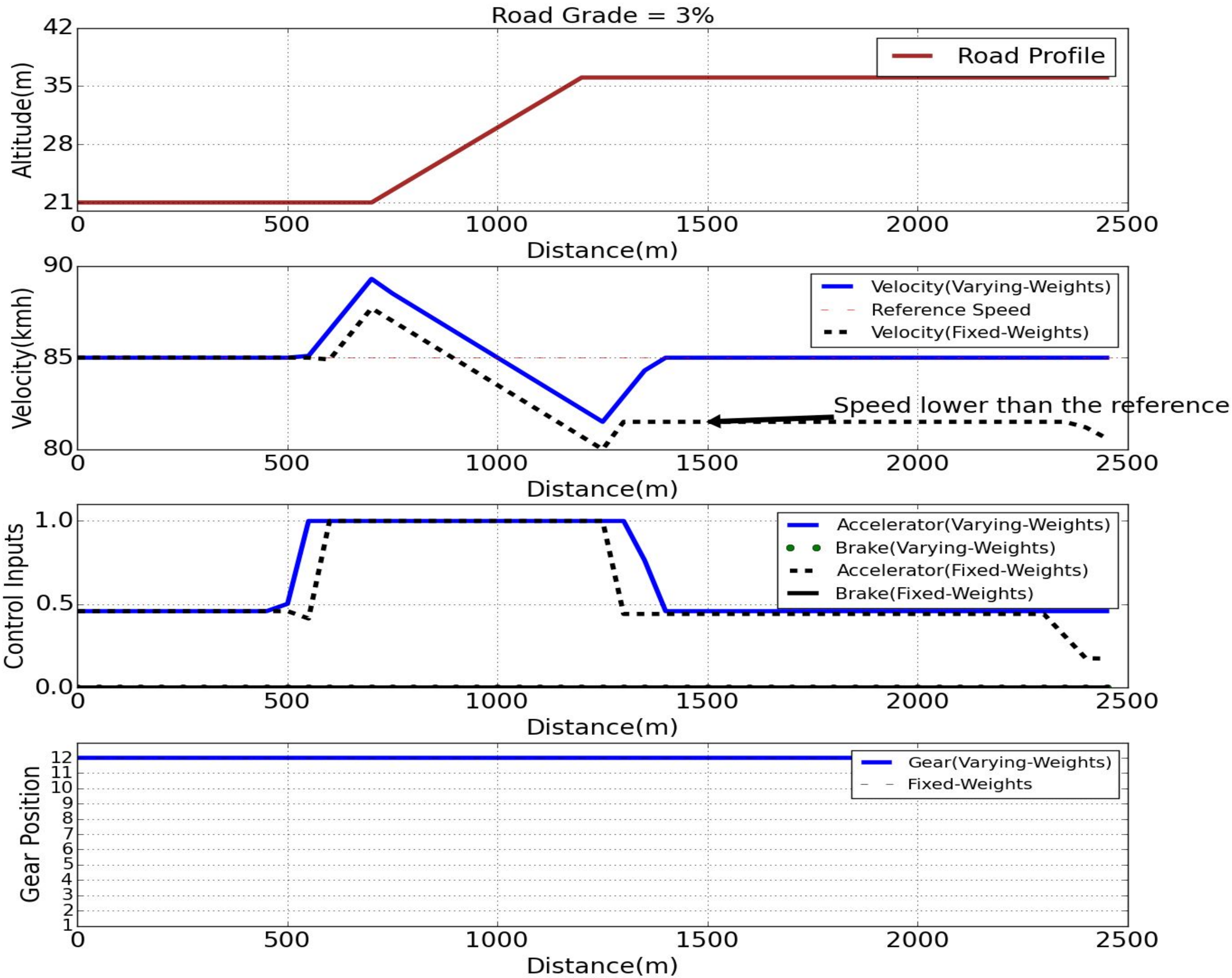
PI Vs Varying-Weights (Uphill)

Gain	Uphill	Value
L_1	Low	1
L_2	Low	2
L_3	High	15
L_4	Nil	0

Desired Behavior	Observed Behavior
Accelerate Before Ascent	☺
Accelerate During Ascent	☺
Fuel Consumption	☺
Minimal Speed Drop	☺
Time	☺

$$\Delta_{fuel}(\%) = \frac{m_{f,VW} - m_{f,PI}}{m_{f,PI}} \times 100 \quad = -0.44\%$$

Performance Analyses Of Fixed-Weights Optimal Control Vs Varying-Weights Optimal Control



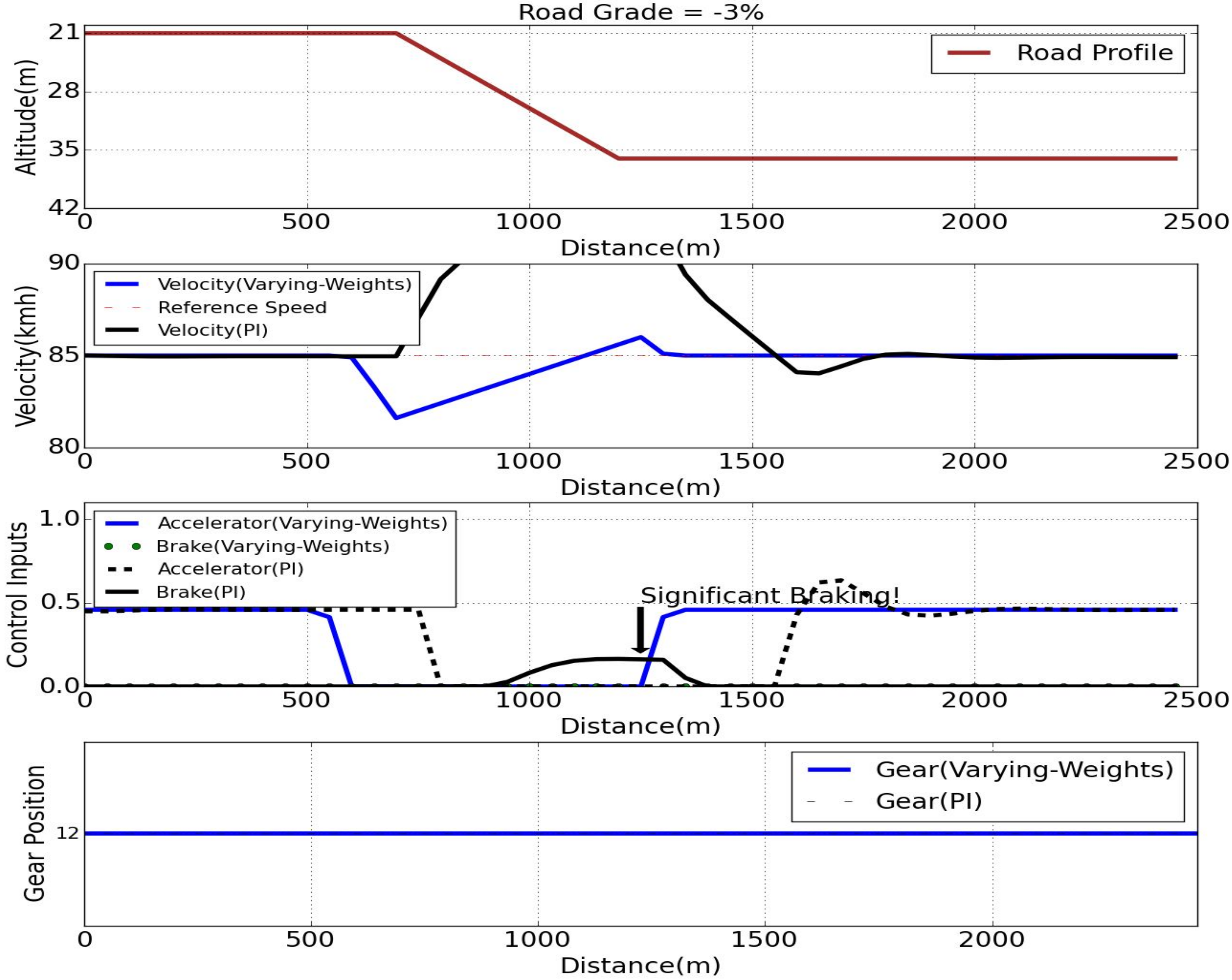
Varying-Weights Vs Fixed-Weights (Uphill)

Gain	FW	VW	Value
L_1	2	Low	1
L_2	5	Low	2
L_3	15	High	15
L_4	100	Nil	0

Desired Behavior	Observed Behavior
Accelerate Before Ascent	
Accelerate During Ascent	
Fuel Consumption	
Minimal Speed Drop	
Time	

$$\Delta_{fuel}(\%) = \frac{m_{f,VW} - m_{f,PI}}{m_{f,PI}} \times 100 = 1.79\%$$

Performance Analyses Of PI Vs Varying-Weights Optimal Control(Fuel Savings = -0.48%)



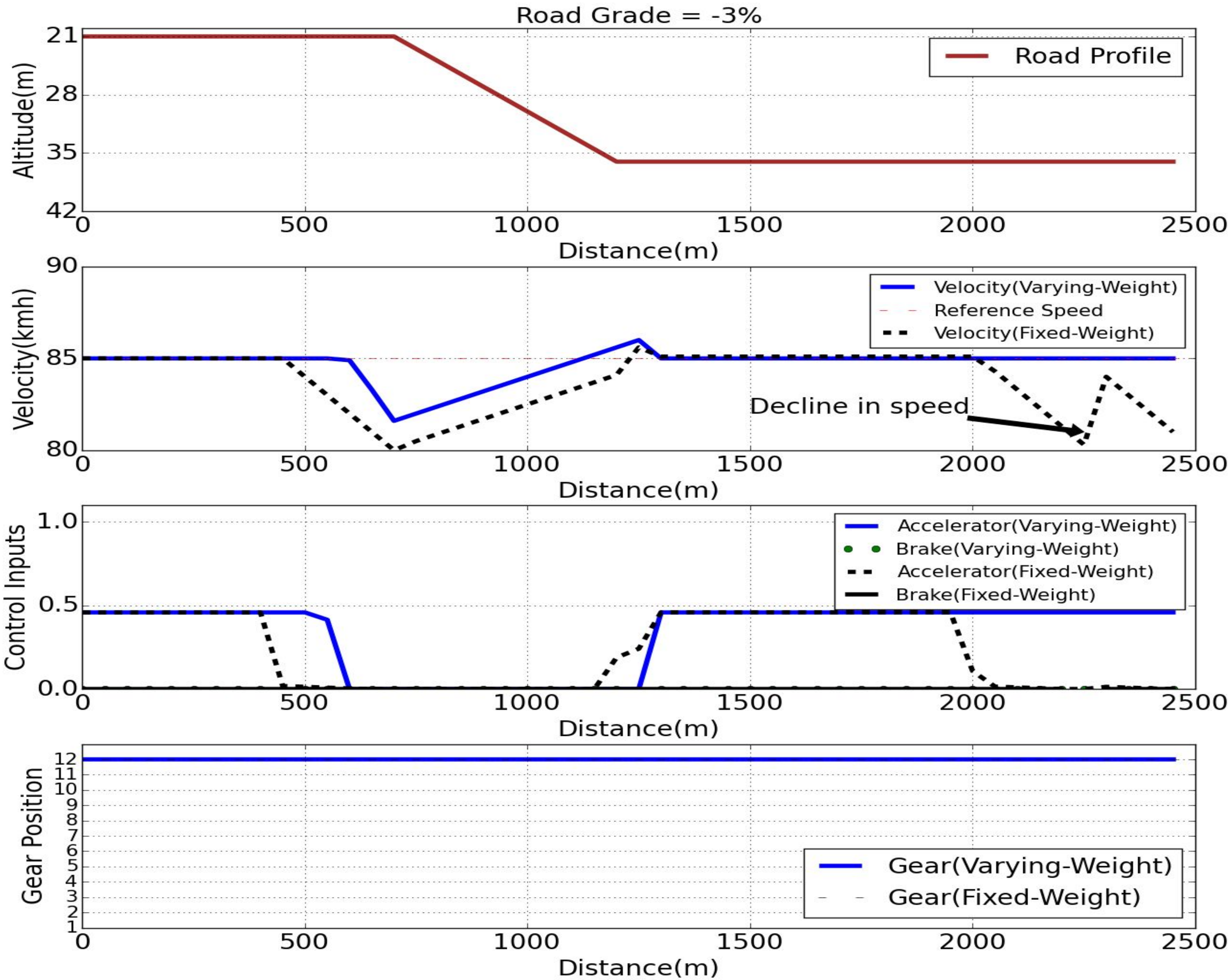
Varying-Weights Vs PI (Downhill)

Gain	VW	Value
L_1	High	2.5
L_2	Low	1
L_3	High	15
L_4	High	100

Desired Behavior	Observed Behavior
Decelerate Before Descent	
Coasting During Descent	
Fuel Consumption	
Minimal Usage Of Brakes	
Time	

$$\Delta_{fuel}(\%) = \frac{m_{f,VW} - m_{f,PI}}{m_{f,PI}} \times 100 \quad = \text{-0.48\%}$$

Performance Analyses Of Fixed-Weight Optimal Control Vs Varying-Weight Optimal Control



Varying-Weights Vs Fixed-Weights (Downhill)

Gain	FW	VW	Value
L_1	2	High	2.5
L_2	5	Low	1
L_3	15	High	15
L_4	100	High	100

Desired Behavior	Observed Behavior
Decelerate Before Descent	
Coasting During Descent	
Fuel Consumption	
Minimal Usage Of Brakes	
Time	

$$\Delta_{fuel}(\%) = \frac{m_{f,VW} - m_{f,PI}}{m_{f,PI}} \times 100 = 1\%$$

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Summary

Terrain	Objective	Conventional Control	FW Control	VW Control
Flat Stretch	Speed Tracking	Good	Poor	Good
Uphill	Speed Drop	High	>VW	Minimal
	Fuel	>FW/VW	<PI/VW	<PI
	Time	High	>VW	Low
Downhill	Speed Increase	High	Low	Low
	Brake Use	High	Low	Low
	Fuel	>FW/VW	<PI & VW	<PI
	Time	Low	>PI/VW	<FW & >PI

Varying-Weights Control is simpler since it needs no pre-processing algorithm!

Thank you!

Acknowledgement

- Advisory Committee:
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  - Dr. Xingyong Song