Sound Transit East Link and Lynnwood Link Aerial Guideway

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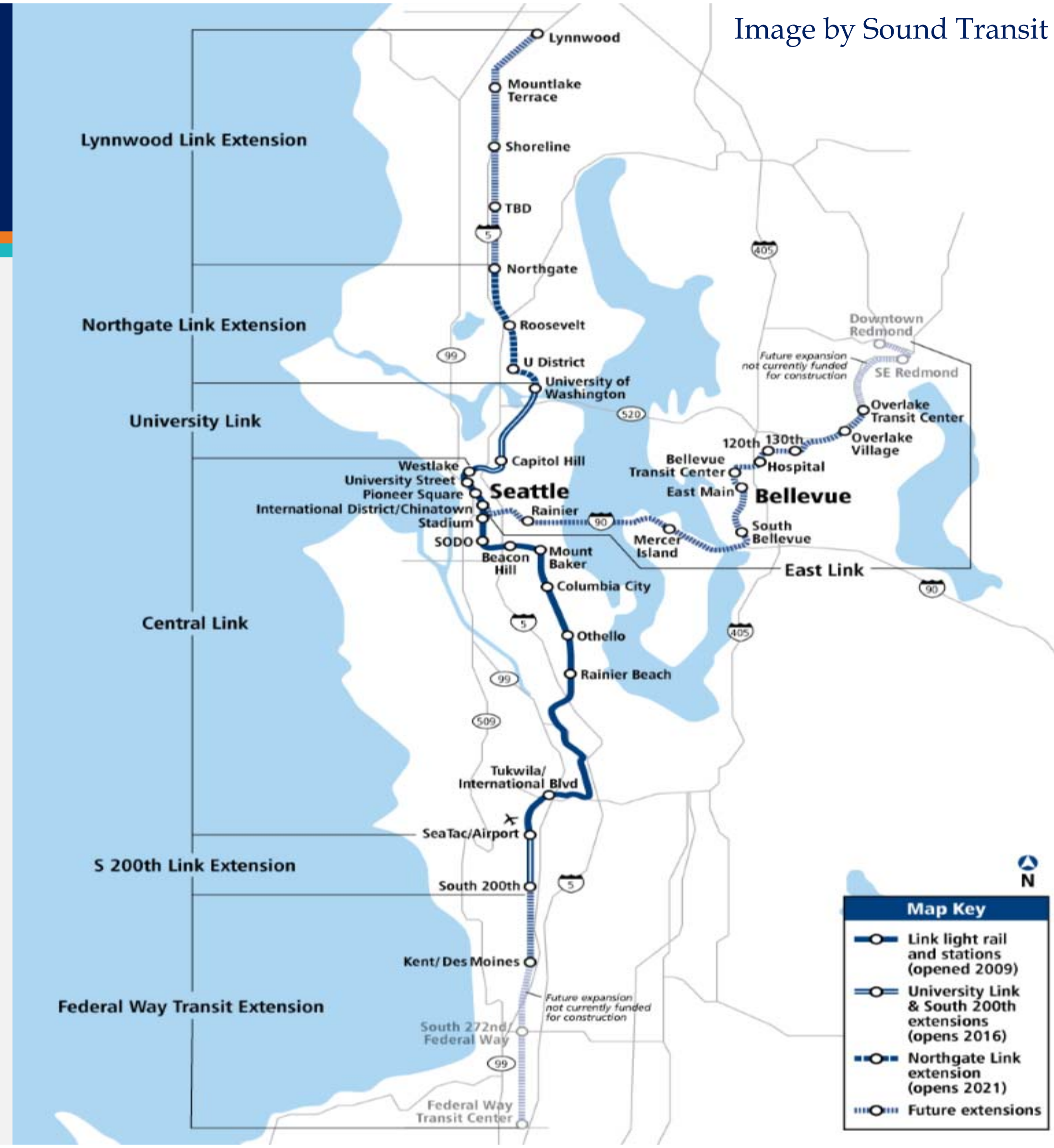
Image by Sound Transit

Overview

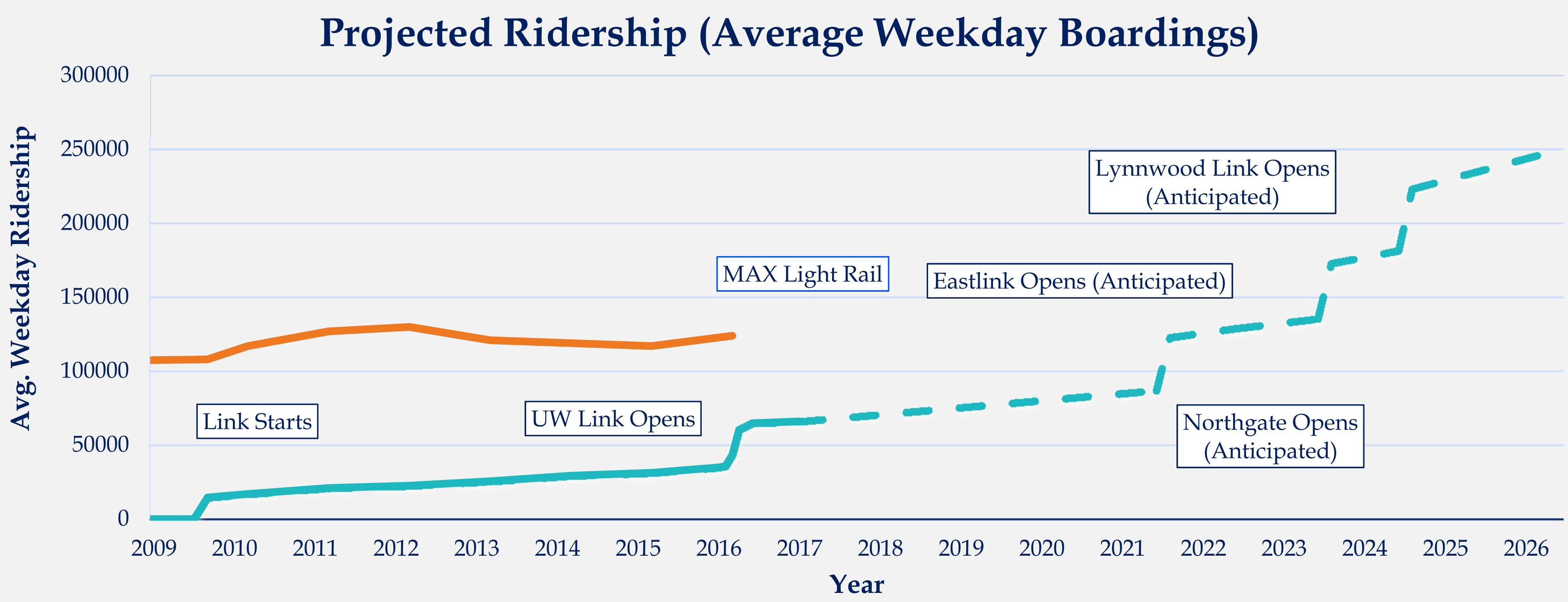
- Sound Transit System
- East Link and Lynnwood Link Overview
- Superstructure – Span Optimization
- Superstructure – Vibration and Deflection Control
- Substructure – Displacement vs. Force Based Design for ODE

ST Light Rail System

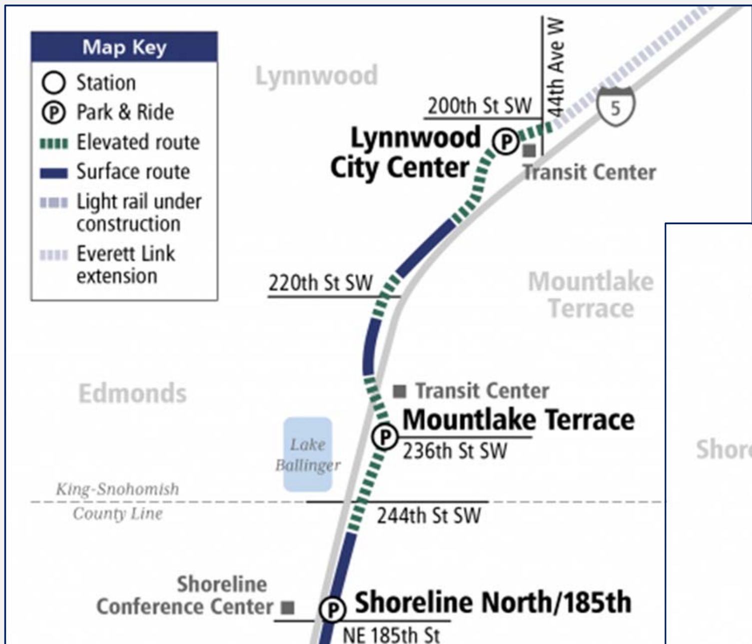
- First Segment (Central Link) opened in 2009
- 20 miles currently in service
- 52 miles total expected by 2024
- 116 miles total by 2041



Projected Ridership for ST Light Rail



Lynnwood Link

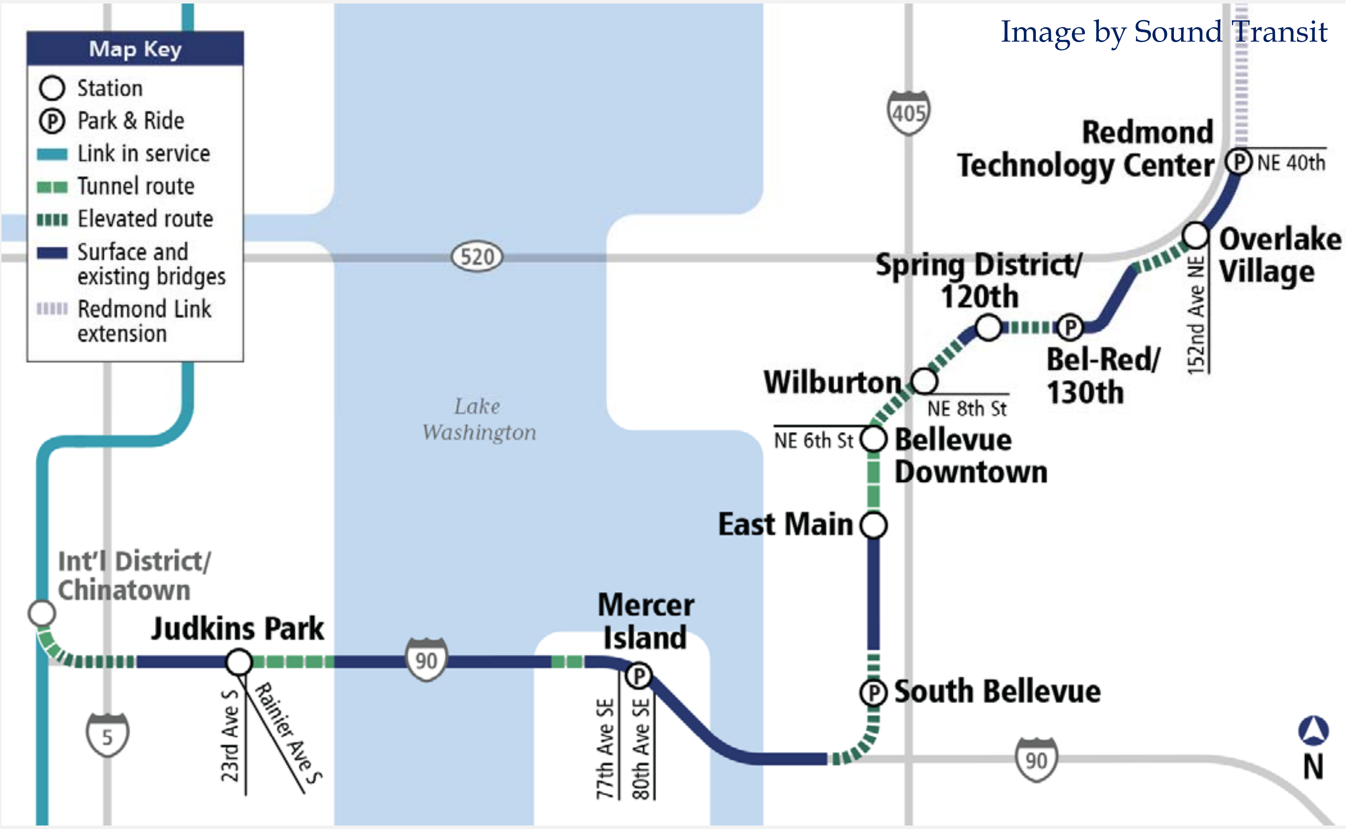


Images by Sound Transit

- $2.8B Program
- Length: 8.5 miles total. 4 mi. of Aerial Guideway
- Start of Service: 2024
- 70,000 daily riders by 2035

East Link

- $3.7B Program
- Length: 14 miles
- Start of Service: 2023
- 50,000 daily riders by 2030
- Connects Seattle to Eastside



East Link Construction Cost

E340:

- $100M
- 1.1 miles
- 0.3 miles Aerial

- 130^{th} Station (At-Grade)
- $90M/mile

East Link Construction Cost

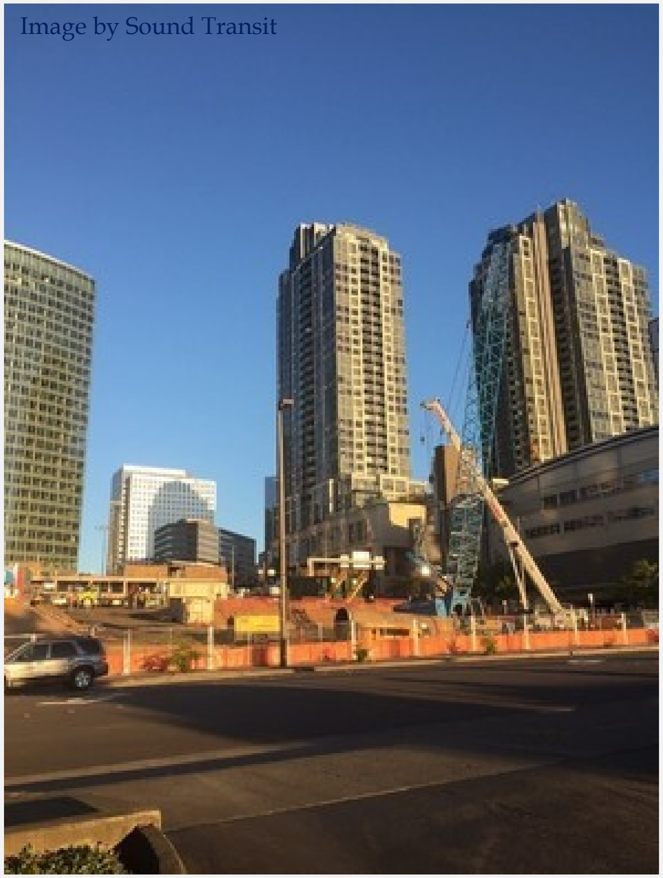
E320:

- $321M Construction Cost
- 2.4 miles total
- 1.1 miles Aerial
- South Bellevue Station (Aerial)

Image by Sound Transit

- $135M/mile

East Link Construction Cost



E330 & E335:

- $430M (Approx.)
- 1.9 miles Total
- 0.5 miles Tunnel
- 0.8 miles Aerial
- East Main, BTC, Hospital, and 120th Stations.
- $225M/mile

East Link Construction Cost

E330 & E335:

Image by Sound Transit

Light Rail Construction Costs

What Drives Const. Cost?

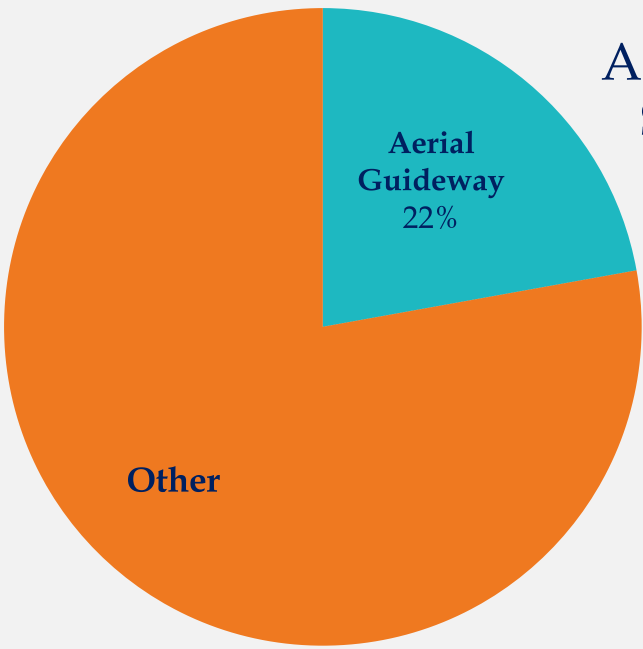
- Tunnel / Trench
- Elevated or Below Grade Stations and Parking Garages
- Aerial Guideway

How to Control Cost?

- Take advantage of existing infrastructure
- At-Grade where possible
- Efficient Structure Types

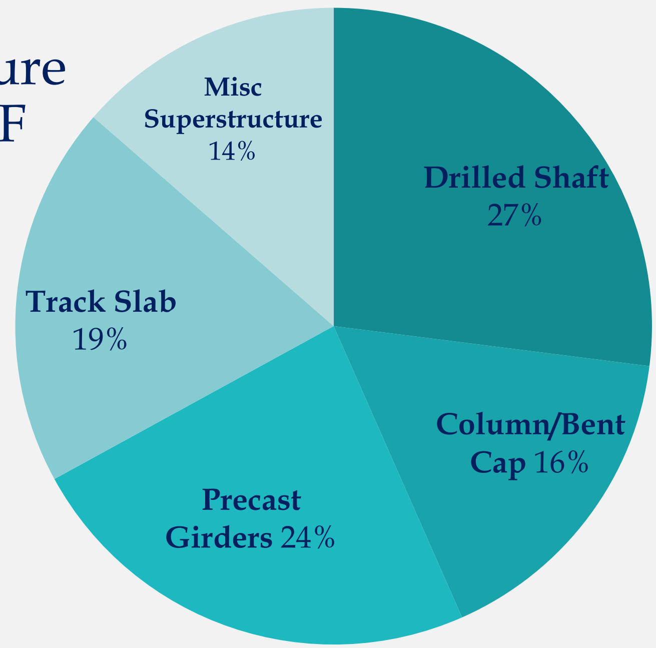
Superstructure – Cost

Total Project Direct Cost



Aerial Guideway Structure
$10,000 - $11,000 per LF

Aerial Guideway Cost Breakdown



Superstructure – Type Selection

PE Selection: Precast Segmental Concrete Box

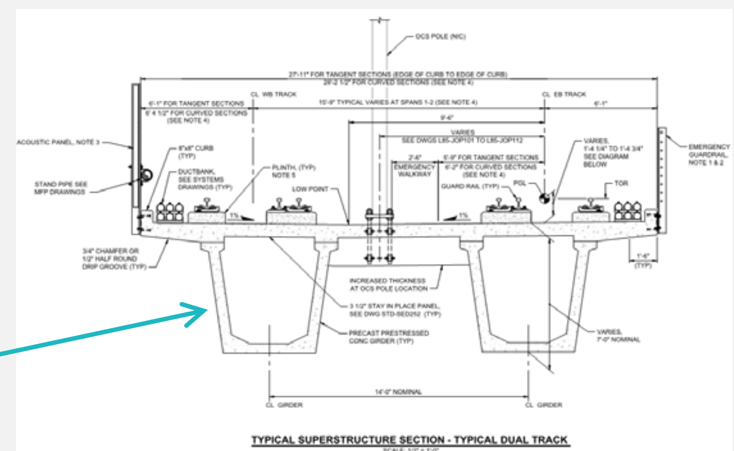
- Utilized on Central Link
- Aesthetics

Central Link

Final Design Proposal: Precast Tub/WF Girders

- Projects Broken Up in Multiple Contracts
- Dual/Single Track w/ Center Platform Station

East Link



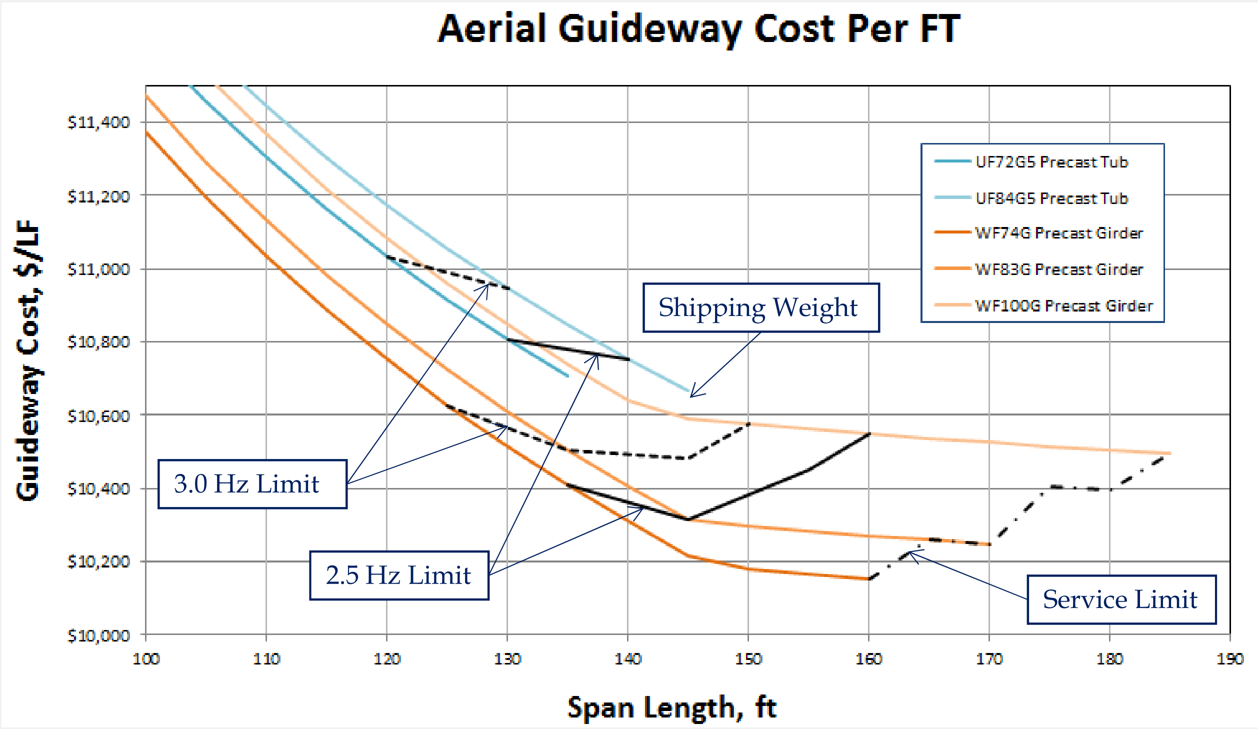
Superstructure – Span Optimization

Precast Girder Type:

- Tubs
  - o Aesthetics
- WF Girders
  - o ~$400/LF Savings

Optimal Span Length:

- Shipping Limit
- Service Design
- *Frequency Requirements*



Superstructure – Vibration and Deflection Control

Current Sound Transit Design Requirements:

- 1st Mode of Natural Frequency
  - Multiple Spans >= 3.0 Hz
  - 1 of 3 Consecutive Spans >= 2.5 Hz
- Deflection (LL + Dynamic) <= L/1000

Other Agencies with Similar Frequency Criteria:

- Massachusetts, Utah, Toronto, Los Angeles, Denver, Phoenix

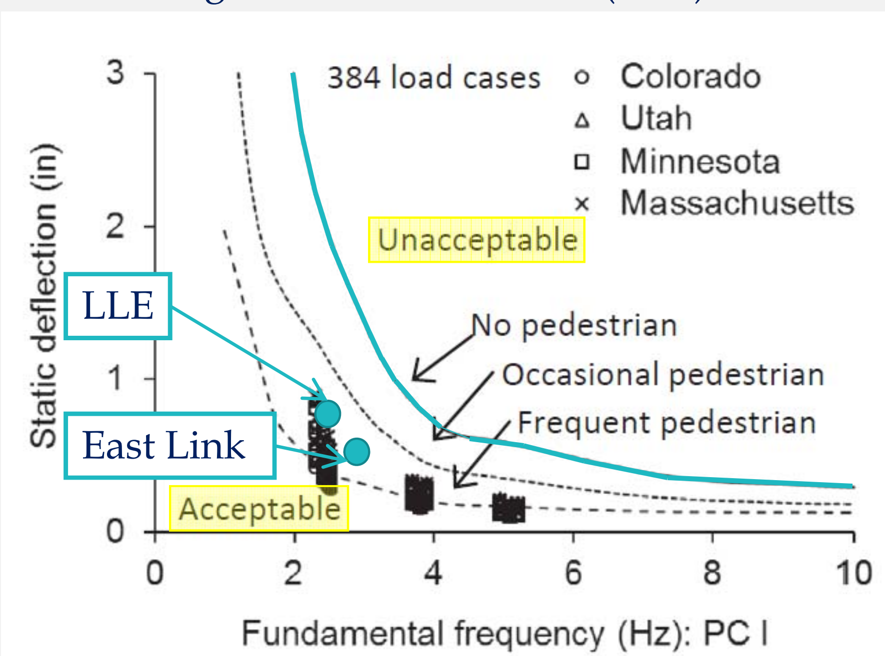
- If frequency is not satisfied, time-history analysis modeling structure, vehicle truck primary suspension and secondary suspension

Is a constant frequency limit the best approach?

Superstructure – Rider Comfort

Control Accelerations by Limiting Deflections:

- NCHRP Research Report 851 – Proposed AASHTO LRFD Bridge Design Specifications for Light Rail Transit Loads (2017)



- UIC (International Union of Railways) 776-2R - Deflection Limits for Keep Vertical Acceleration < 0.1g

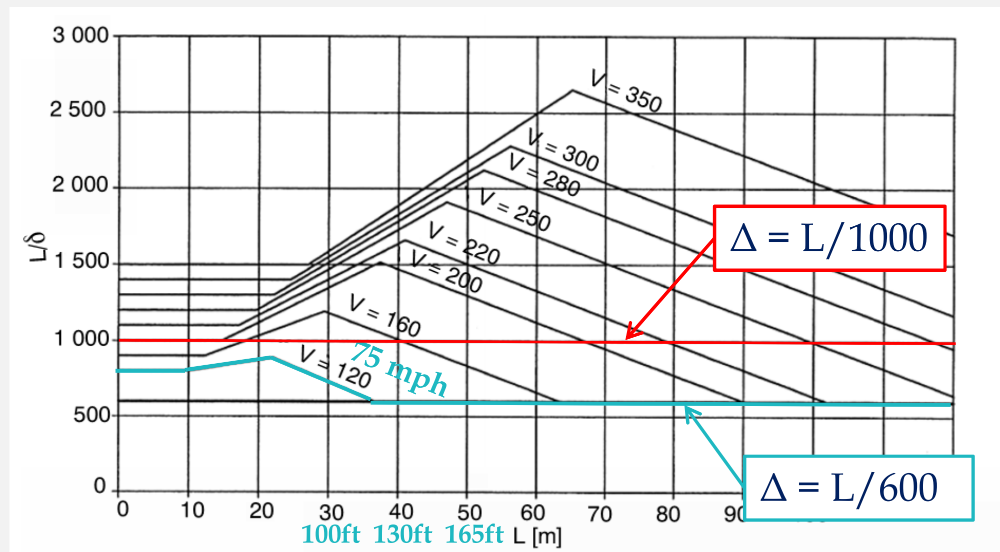


Fig. 5 - Maximum permissible vertical deflection δ for rail bridges corresponding to a permissible vertical acceleration of b_v = 1/ms^2 in the coach

Superstructure – Rider Comfort

Structure Vertical Acceleration Criteria:

- At Deck Level
  - Vert Acceleration < 0.5g
  - Recommended by UIC and FRA for operating safety
- At Passenger Level

UIC 776-2R Table 2: Indicative levels of comfort

Level of Comfort	Vertical Acceleration (m/s^2)	Vertical Acceleration (g)
Very Good	1.0	0.10g
Good	1.3	0.13g
Acceptable	2.0	0.20g

Measured Vertical Deck Acceleration in CSI Bridge Model:

Aerial Guideway Vibration Control - WF Girder (Tubs Similar)

Dual Track Girder Type	Span Length (ft)	Vertical Frequency (Hz)	Controlling Criteria	Max Deck Acceleration (g)
WF74G	135	2.5	Frequency	0.04
WF74G	160	1.9	Service	0.08
WF83G	145	2.5	Frequency	0.04
WF83G	170	1.9	Service	0.06
WF100G	160	2.5	Frequency	0.05
WF100G	185	1.9	Service	0.07

Superstructure – Limit Vibrational Amplification

Frequency Limits to Prevent Resonance:

- Loading Frequency:

  Vehicle Speed = 55 mph = 81 ft/s

  Span Length = 130 ft

  Loading Frequency = V/L = 0.6 Hz << 1.9 Hz

  Service Limit Span Length Frequency

  Approx. Dynamic Magnification Factor = $1/(1-(0.6\text{Hz}/1.9\text{Hz})^2) = 1.10$

- Resonance with Light Rail Vehicle:

  Car Body Resonance Frequencies= 1.5 to 2.0 Hz

  Truck Related Resonance Frequencies = 4.0 to 5.0 Hz (or higher)

Superstructure – Vibration and Deflection Control

Summary:

- Frequency criteria is controlling span length on Sound Transit projects
- Based on research by Sound Transit and HNTB|Jacobs, a deviation was granted to decreased frequency requirement from 3.0 Hz down to 2.5 Hz
- Still concerns with frequencies < 2.5 Hz resonating with light rail vehicle

Looking back to a path forward

Ballard Bridge Seismic Retrofit Study 1993
City of Seattle

- Changed seismic design approach during project from Force Based Design (FBD) to Displacement Based Design (DBD)
- *Seismic Design and Retrofit of Bridges* Priestley, Seible and Calvi 1996

Ballard Bridge 2017

Sound Transit Central Link Light Rail

Timeline:	Sound Transit Founded	1996
	Final Design	2002
	Opened	2009

Seismic Design Parameters:

- Two Level Earthquake Design –
  - Maximum Design Earthquake (MDE) 2500 yr
  - Operating Design Earthquake (ODE) 150 yr
- Force Based Design (FBD)

Column Design:

- Seismic Load Combinations (MDE and ODE) control column and foundation size and strength

Central Link: Seattle to SeaTac
Aerial Guideway: 4.2 miles

Sound Transit East Link Extension

Timeline:	ST 2 Approved	2008
	Final Design	2012 - 2015
	Opening	2023

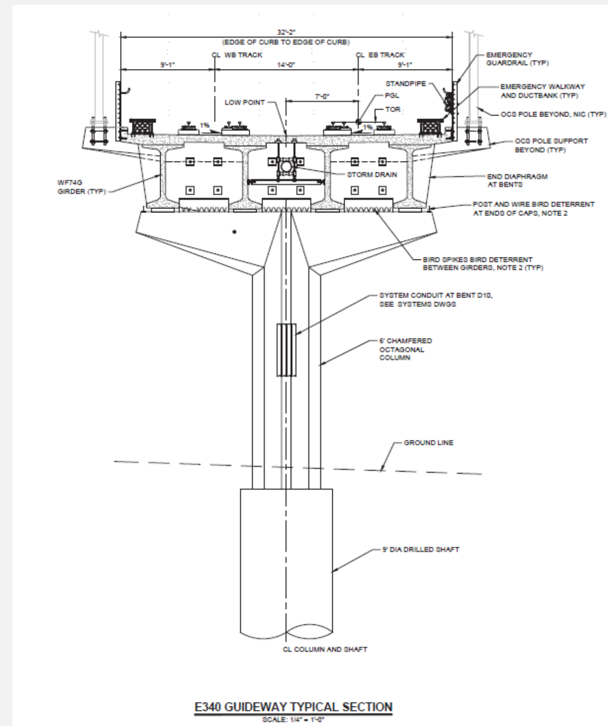
2012 Seismic Design Parameters

Two Level Earthquake Design

- MDE Displacement Based Design per AASHTO SGS
- ODE Similar to Central Link

2015 Change to Displacement Based Design (DBD) for ODE

- Results of FBD for ODE discovered during Eastlink Design
- *Performance Based Seismic Bridge Design* NCHRP Synthesis 440, 2013



East Link Extension
Aerial Guideway: 1.8 miles

ODE Column Displacement Capacity

ODE Performance Goal: Fully Operational

ODE Column Displacement Capacity is the lesser of:
(Hose and Seible 1999- from NCHRP 440)

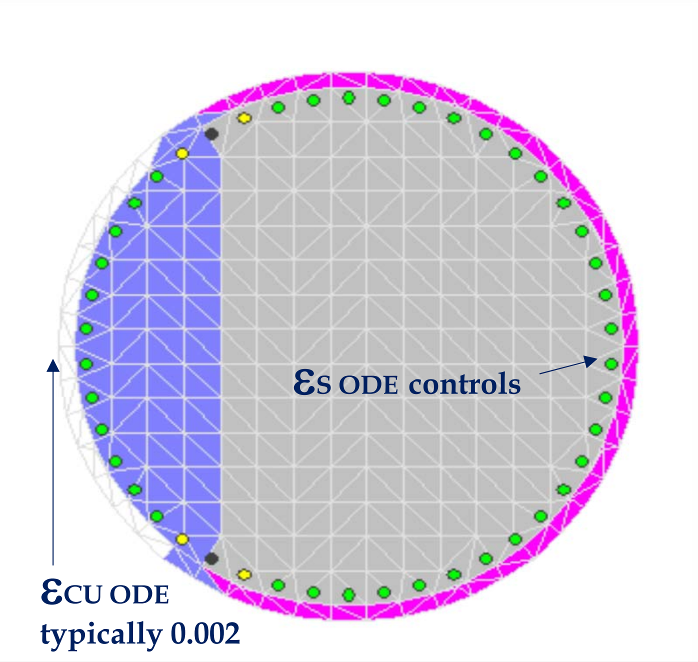
- $D_{U\ ODE} = D_Y + D_{P\ ODE}$, $D_{P\ ODE} < 0.2\ D_Y$
  use analytical plastic hinge per AASHTO SGS
  and ODE strain limits:

$\varepsilon_{S\ ODE}$	< 0.005	reinforcing (controls)
$\varepsilon_{CU\ ODE}$	< 0.0032	concrete cover

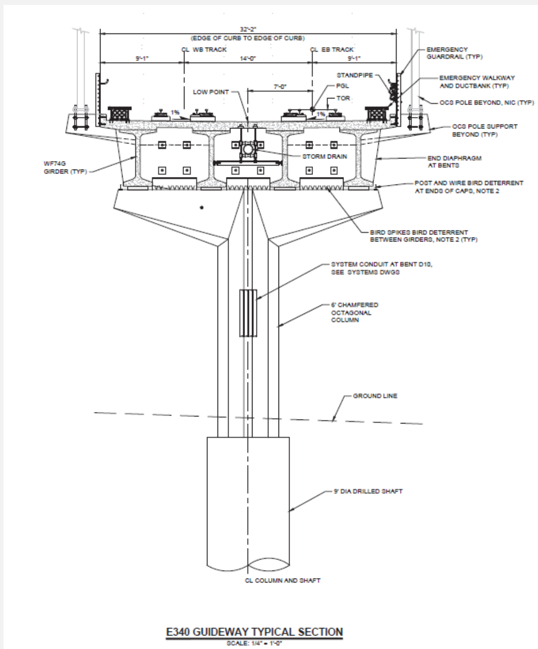
- 1% Column Drift

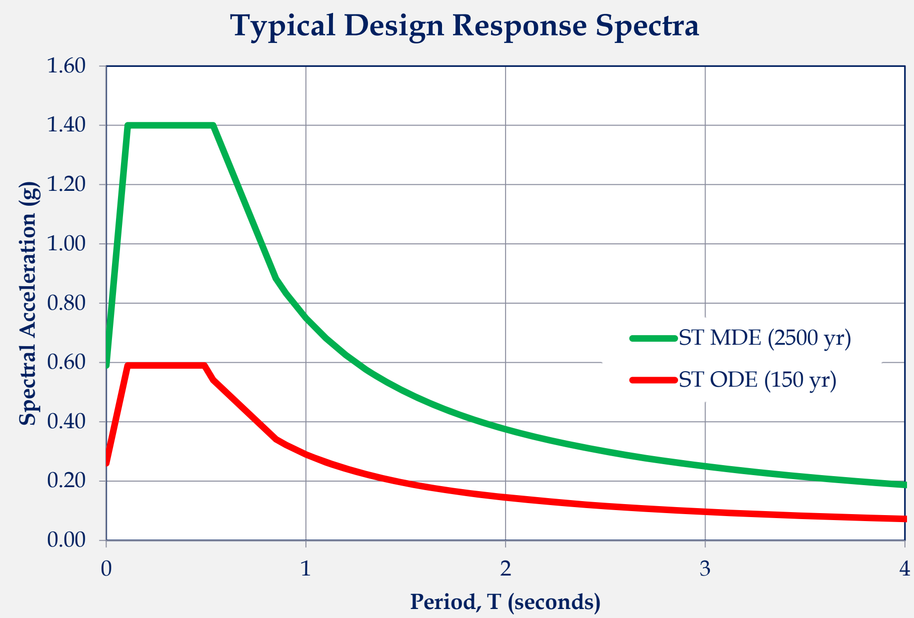
MDE Displacement Capacity per AASHTO SGS

Column Cross Section at Base of Column



Seismic Analysis and Demand





Typical Guideway Bent:

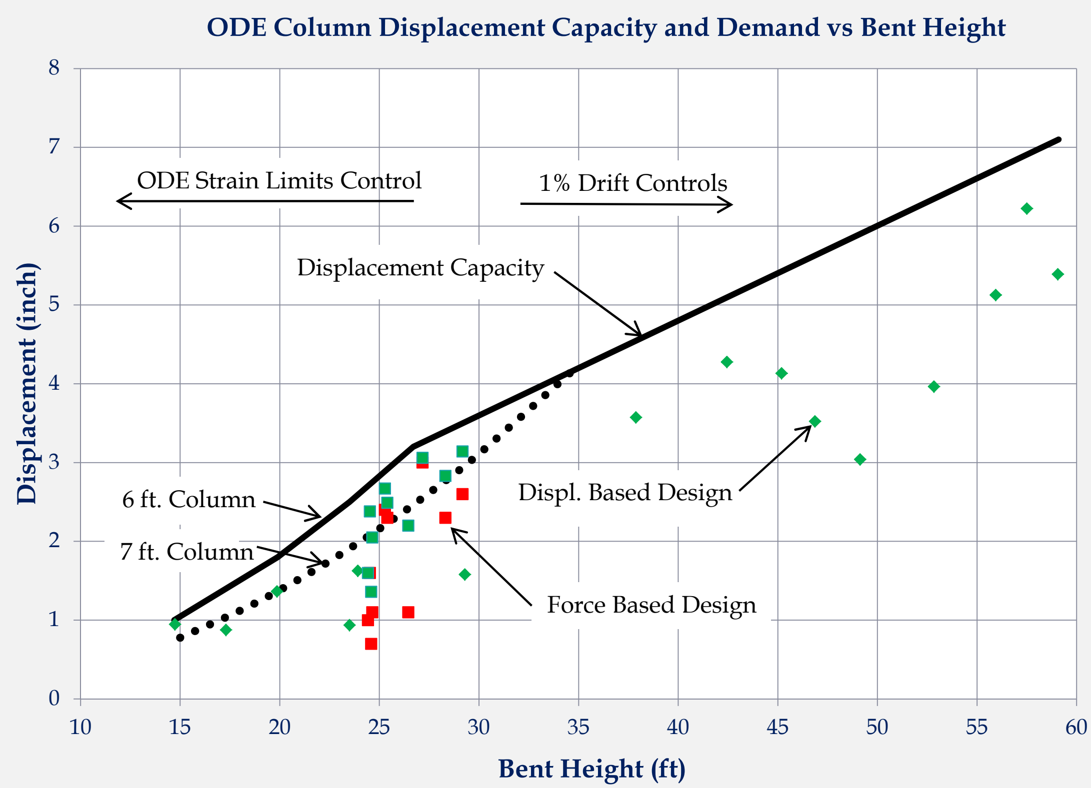
- Plastic Hinge at Base of Column
- Capacity Protect Drilled Shaft

Modal Seismic Analysis

- "Equal Displacement Assumption"

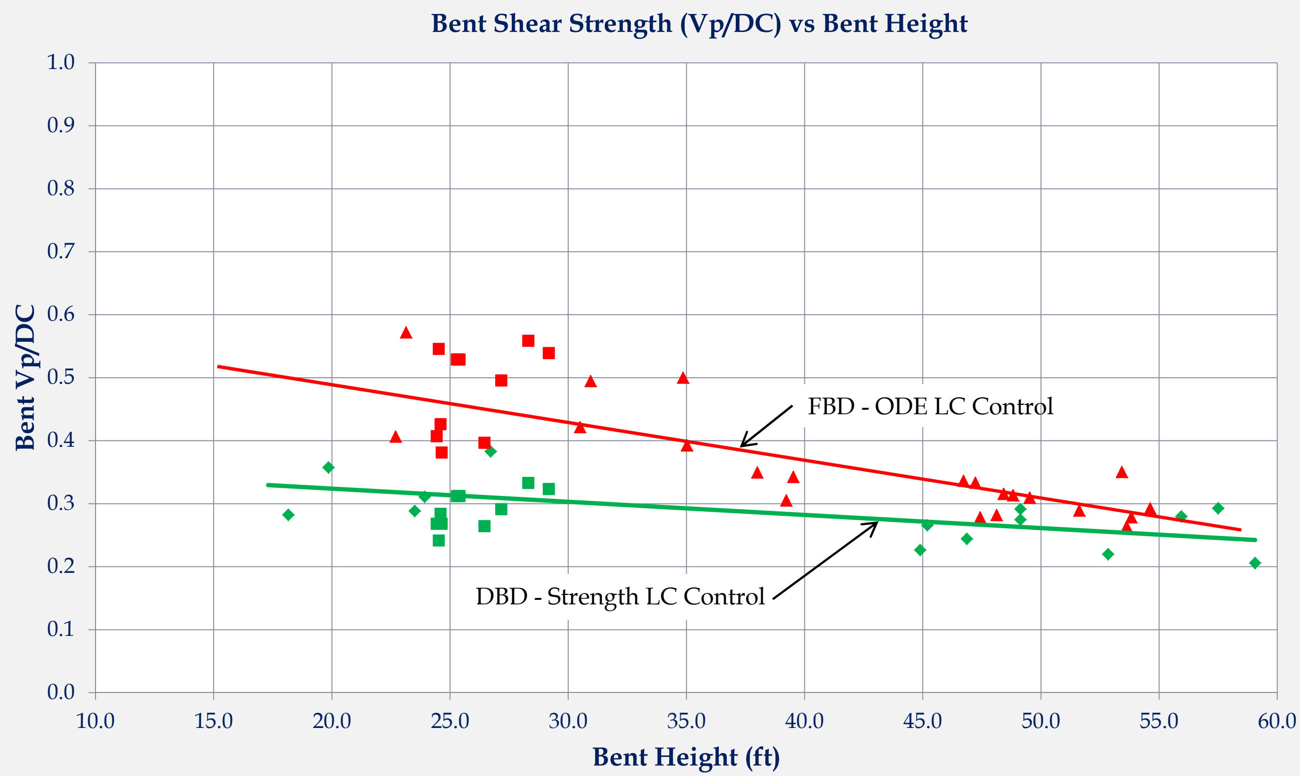
Seismic Design
ODE Displacement Capacity vs Demand

- Drift limit control capacity for tall columns
- $D_{U\,ODE} = D_Y + D_{P\,ODE}$ controls capacity for short columns
- Displacement capacity cannot be adjusted with reinforcing
- Capacity limit useful for sizing columns during preliminary design



Seismic Design
Column Lateral Strength Comparison

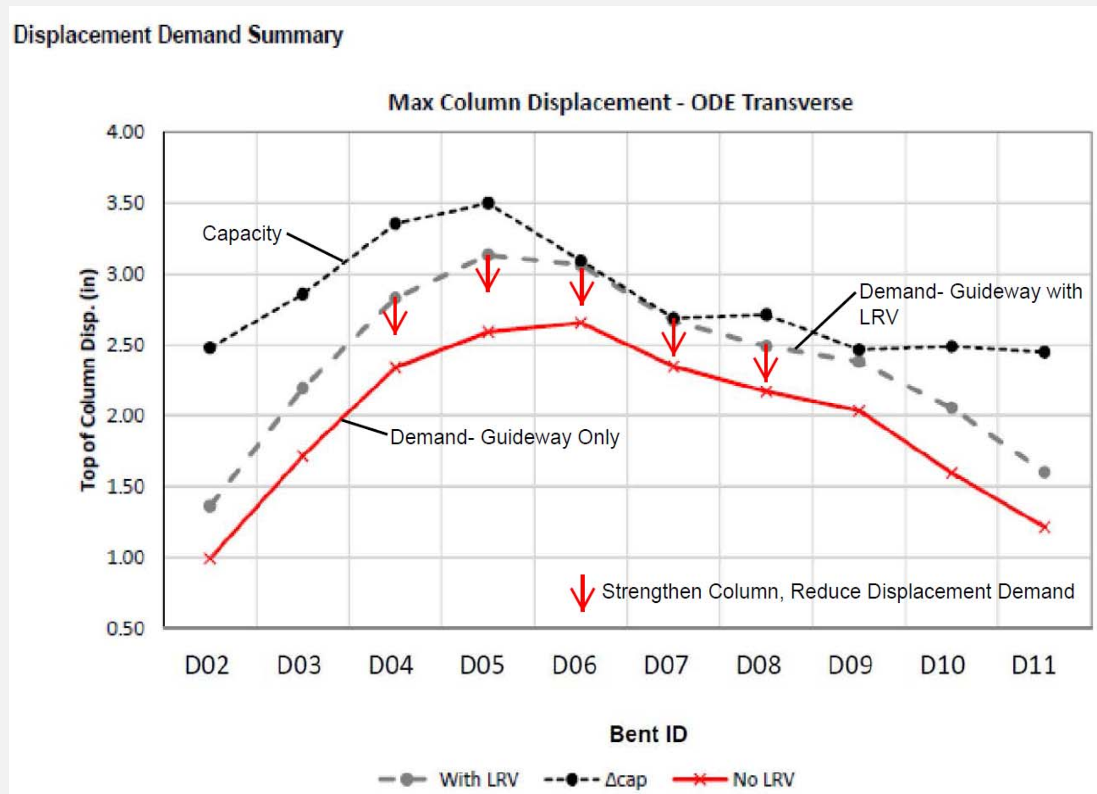
- Displacement Based Design reduces lateral design forces in short column



East Link
Segment D ODE Redesign

Span Layout	11 spans- 1165 ft.
FBD 2014	7 ft. columns, 10 ft. shafts
ODE Redesign 2016	6 ft. columns, 9 ft. shafts

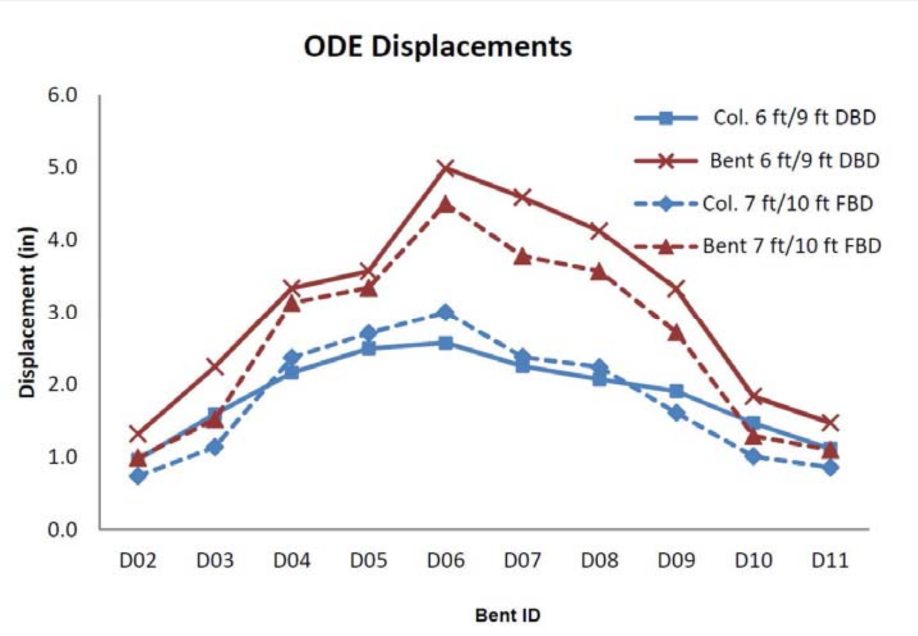
- ODE Column Displacement Capacity is independent of column reinforcing
- Designed for LRV- increased displacement demand about 20%
- ODE Column Displacement demand can be reduced by increasing reinforcement

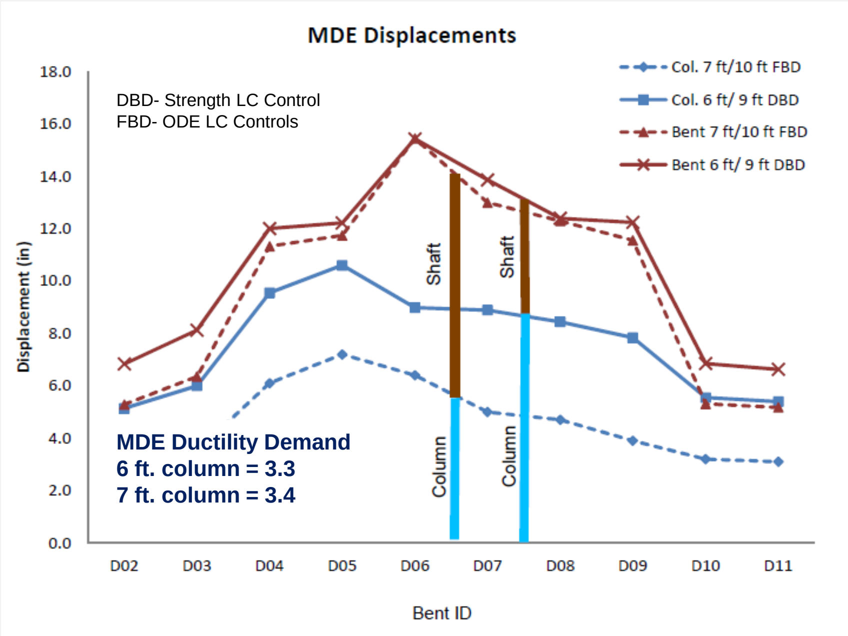


East Link
Segment D ODE Redesign

Seismic Displacement Demand – Change to ODE Displacement Based Design:

- Smaller columns and shafts, similar bent displacement demands
- Similar ductility demand = D_U / D_Y, less foundation movement





Seismic Design
Savings and Take Aways

ODE Displacement Based Design Savings:

- 15 to 20% substructure concrete
- 40 to 50% substructure reinforcing
- Estimated savings: $ 3-5 million/mile for aerial guideway

Take Aways:

- Change takes time
- More engineering costs less than more construction
- Displacement based design is being used for Lynnwood Link Extension – 4 miles of Aerial Guideway

Guideway Segment	Locations	Average Quantities: Column Dia.	Column Rebar	Shaft Dia.	Shaft Rebar
E320 FBD	46	6.5 ft.	65 -#11	9.5 ft.	110 -#11
E335 DBD	32	6 ft.	40 -#11	9 ft.	80 -#11
E340 FBD	10	7 ft.	60 -#11	10 ft.	120 -#11
E340 DBD	10	6 ft.	35 -#11	9 ft.	70 -#11

East Link Quantity Comparisons

Acknowledgements

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Questions?