Appendix E.

TRAFFIC AND SAFETY TECHNICAL REPORT

Santa Fe PEL C-470 to I-25

TRAFFIC AND SAFETY TECHNICAL REPORT

December 2021

Santa Fe PEL
C-470 to I-25

TRAFFIC AND SAFETY TECHNICAL REPORT

Prepared for:

CDOT

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December 2021

ACRONYMS AND ABBREVIATIONS

CDOT	Colorado Department of Transportation
CFI	Continuous Flow Intersection
DRCOG	Denver Regional Council of Governments
FHWA	Federal Highway Administration
HOV	High-Occupancy Vehicle
HSM	Highway Safety Manual
ITS	Intelligent Transportation Systems
LOS	Level of Service
ML	Managed Lane
MPH	Miles Per Hour
MVMT	Million Vehicle Miles Traveled
NCHRP	National Cooperative Highway Research Program
PEL	Planning and Environmental Linkages
RTD	Regional Transportation District's
TDM	Travel Demand Model
TIP	Transportation Improvement Program
TRB	Transportation Research Board
V/C	Volume-to-Capacity Ratio
VHD	Vehicle Hours of Delay
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

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1. Introduction and Study Area

This memorandum documents the traffic and safety evaluation process and outcomes of the *Santa Fe Drive Action Plan (C-470 to I-25) (A Planning and Environmental Linkages Study)* (Action Plan). This memorandum presents the outcomes of the Level 2A and Level 2B screening process. Existing traffic operational and safety conditions are documented in the *Santa Fe PEL (C-470 to I-25) Corridor Conditions Report* (Corridor Conditions Report) (CDOT, 2020). Detailed analysis of the existing crash conditions is provided in Appendix H of the Corridor Conditions Report (Safety Analysis and Recommendations Report).

1.1 Traffic Analysis Area

The project limits for the Planning and Environmental Linkages (PEL) study encompass the Santa Fe Drive corridor from C-470 to I-25. The corridor traverses Arapahoe County, City and County of Denver, Douglas County, City of Englewood, City of Littleton, and City of Sheridan, and is a mix of urban expressway with grade-separated interchanges, urban principal arterial with signalized intersections, and suburban principal arterial with signalized and unsignalized intersections. The Regional Transportation District (RTD) light rail transit (LRT) Southwest Corridor runs parallel to Santa Fe Drive the length of the corridor, next to the Consolidated Main Line freight rail corridor. North of Bowles Avenue to I-25 the corridor cross-section includes a managed lane in each direction that is restricted to high-occupant vehicles during the peak period in the peak direction. The South Platte River runs adjacent to the corridor to the west for the length of the study area. The Mary Carter Greenway shared use bicycle and pedestrian trail exists along the South Platte River. The immediate corridor extents are highlighted orange in Figure 1.

2. Analysis Methodology

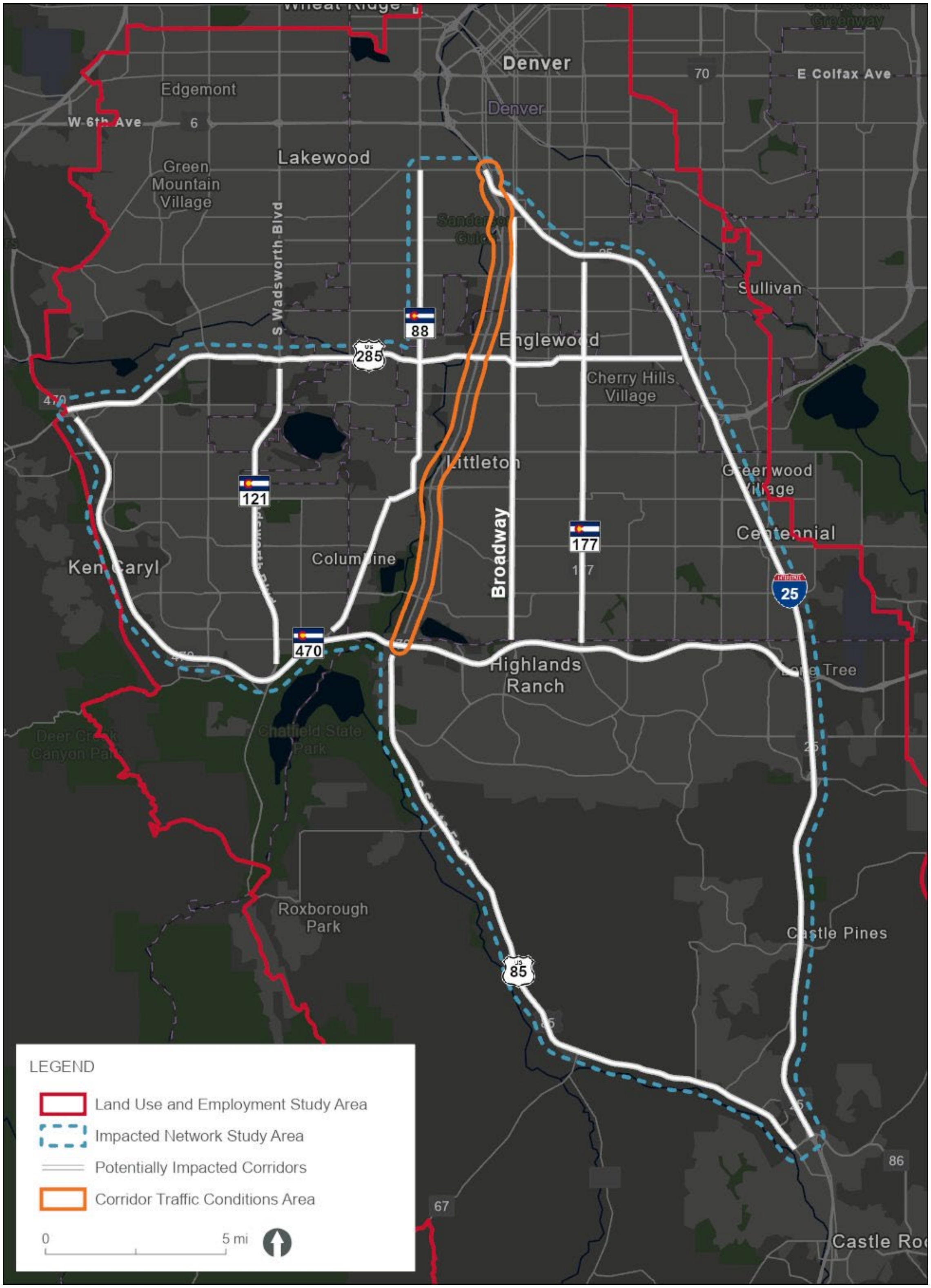
2.1 Traffic Analysis Methodology

Traffic analysis for the Action Plan was conducted using a combination of travel demand modeling and deterministic, macroscopic corridor and intersection capacity analysis tools.

Travel demand modeling was completed using the Denver Regional Council of Governments (DRCOG) regional travel demand model (TDM), also known as FOCUS 2.2. The model meets federal and state planning process requirements, is calibrated and validated by DRCOG, and was used to forecast future travel demand for the Action Plan's planning horizon year of 2040. The TDM methodology follows these general steps:

1. Review base year and future year model networks at the project level
2. Refine base year and future year model networks where errors are identified during review
3. Complete base and future year scenario model runs
4. Adjust future year model forecasts using post-processing methodology

Figure 1. Corridor and Network Study Areas



The 2020 interim year DRCOG planning model was used as a framework for the Action Plan base year model. The 2020 roadway network was reviewed and updated in the study area, as necessary, to match existing conditions per aerial maps and site visits. The 2020 socioeconomic assumptions were reviewed at a high level to identify any egregious errors, with no adjustments to the socioeconomic inputs determined to be necessary. Existing traffic count data was compiled and factored to year 2020, using historic traffic count data and/or average annual growth calculated for the 2020 to 2040 period, for comparison of the future year model outputs to the base year model outputs.

As with all travel demand forecasting models, the DRCOG Focus model cannot be expected to provide precise traffic volume forecasts throughout the roadway system due to the complexity of the real world and the inherent uncertainty of predicting the future. Per industry practice, the model's traffic volumes were adjusted for each of the model runs, across all levels of PEL study process screening, based on actual traffic counts. The methodology of adjustment compared the base year model's predicted traffic volumes to actual traffic counts throughout the project area. These comparisons highlighted the expected variation associated with the model's representation of travel conditions along roadways in the region. Future year daily traffic forecasts were adjusted based on percentage and absolute differences between the existing year model and actual traffic counts, as prescribed in the Transportation Research Board's (TRB) publication NCHRP 765 post-processing adjustment methodology. This method forms Step 4 of the above outlined process.

Household and employment totals and growth projections from year 2020 to year 2040 for the DRCOG planning region are illustrated in Table 1. Growth in the region is expected to continue to be strong over the next 20 years at about 30% for both households and employment, or about 1.3% annually.

Table 1. Travel Demand Forecasting Lane Use Projections

Land Use	Year 2020	Year 2040	Change
Households	1,421,000	1,837,400	+416,400 (+29%)
Employment	1,828,500	2,395,200	+566,700 (+31%)

Source: DRCOG Focus Model, 2017

The DRCOG planning model was utilized at Level 1 screening to identify regional impacts of potential corridor improvements and assess the future demand for the corridor. Screening at Level 2A applied post-processed outputs from the TDM to assess corridor-wide conditions, with intersection and interchange capacity analysis developed using the Federal Highway Administration (FHWA) Capacity Analysis for Planning of Junctions (Cap-X) tool. At Level 2B the post-processed TDM forecasted traffic volumes were used to develop corridor and spot location capacity analysis using Trafficware's Synchro v10 capacity analysis software.

2.2 Safety Analysis Methodology

The safety analysis for the Action Plan was conducted using the FHWA *Highway Safety Manual* (HSM) methodology. Further information about the methodology and inputs used to determine the baseline/existing conditions is available in the *Safety Analysis and Recommendations Report* (September 2020), which is included as Appendix H of the Corridor Conditions Report (CDOT, 2020).

2.3 Overview of Alternatives Evaluation Process

Through the Santa Fe PEL study process, numerous concepts to improve traffic operations, safety, and multimodal mobility were considered and evaluated through a multi-step evaluation process:

1. Level 1 Purpose and Need Screening

Reasonable and feasible concepts evaluated qualitatively against the Purpose and Need. Travel demand modeling tasks were undertaken, however as a primarily qualitative evaluation, no detailed operational or safety analysis was completed for Level 1 screening. Concepts at this level generally featured a broad spectrum of:

- Cross-sections
- Roadway classification
- Intersection/Interchange types
- Multimodal treatments
- Technology concepts

2. Level 2 Comparative Screening

The Level 2 screening utilized a two-stage process to cross-cut location-specific and corridor-wide options. At Level 2A qualitative and quantitative traffic and safety metrics were developed for evaluation of options. At Level 2B a complete quantitative analysis was undertaken for traffic and safety metrics:

- **Level 2A – Infrastructure Options.** At this level, options were more location-specific within the following categories:
  - General classification and cross-sections
  - Spot locations
  - Intersections/Interchanges
  - Multimodal
- **Level 2B – Corridor Alternatives.** At this level, the results from Level 2A were applied to develop packaged corridor alternatives with a common theme base. The Level 2B themes were:
  - Theme 1: Safety and Operations

  - Theme 2: Corridor Access Focus
  - Theme 3: Premium Multimodal
  - Theme 4: Adaptability/Flexibility

From a traffic operations and safety perspective, the alternatives were developed/informed at each level by the identified issues observed on the corridor on the existing conditions analysis. The primary concerns identified in the Corridor Conditions Report (CDOT, 2020) were intersection-related crashes and overall crash rate, peak period travel times and travel time reliability, and congestion bottlenecks due to delay at major intersections.

3. No Action Alternative

Common across all levels of screening, the No Action represents what would happen if no improvements were made to the Santa Fe study corridor. This alternative represents the baseline conditions against which the other options and alternatives are compared. The No Action does include the following roadway improvements along the corridor from the Fiscally Constrained Regional Transportation Plan:

- I-25 and Alameda Avenue Improvements (DRCOG TIP)
  - Interchange reconstruction with new bridge over South Platte River
  - Local street improvements to Lipan Street
  - Pedestrian and bicycle facility improvements and grade-separated South Platte River Greenway path
- Kentucky Bridge over South Platte and New Santa Fe Signal (privately funded)
- Pedestrian/Bicyclist Bridge at Jewell Avenue (Denver Capital Improvement Program)
  - Grade-separated pedestrian/bicycle bridge over Santa Fe
- Dartmouth Sidewalks Santa Fe to Zuni (Safer Main Streets grant for Englewood)
- Oxford Avenue Pedestrian/Bicyclist Bridge (DRCOG TIP)
  - Grade-separated pedestrian/bicycle bridge over Oxford Avenue east of Santa Fe
- Mineral Avenue Quadrant Road at Santa Fe (DRCOG TIP)
- Mineral Mobilityshed Improvements (DRCOG TIP)
  - Pedestrian/bicyclist improvements east of Santa Fe
- New Traffic Signal on Santa Fe south of Mineral (privately funded)
- County Line Road at Santa Fe Intersection Improvements (DRCOG TIP)
- US 85 Highlands Ranch Parkway to County Line Road Improvements (DRCOG TIP)
- Santa Fe widening from 4 to 6 lanes
  - Replacement and widening the US 85 bridge over C-470, including adding a pedestrian/bicyclist trail across C-470
  - New and improved signal interconnection and ITS infrastructure
  - Grade separation of the C-470 trail and High Line Canal trail under US 85
  - Transit stop enhancements

Projects **near the corridor** that were included in the 2040 No Action TDM network:

- Dartmouth Ave at Platte River Drive Intersection Improvements (Englewood HSIP)
- US 285 and Federal Ramp Widening (CDOT)
- Hampden & Broadway Interchange Improvements (DRCOG TIP)
- Broadway Intersection Improvements in Littleton (Littleton)
  - Safety and capacity improvements for vehicular and multimodal movements
  - Traffic signal upgrades
- Platte Canyon Drive Intersection Improvements (Littleton)
  - Safety and capacity improvements at Bowles and Mineral
- US 85 Titan Road to Highlands Ranch Parkway (DRCOG Regional Transportation Plan 2025-2034)
  - Santa Fe widening from 4 to 6 lanes
  - Intersection improvements at County Line Road

A regional snapshot of the network performance is provided by vehicle miles traveled (VMT) and vehicle hours traveled (VHT) in the DRCOG region. Table 2 illustrates the regional growth in VMT and VHT from the base year 2020 model to the 2040 No Action model (raw model data). From 2020 to 2040, daily VMT and VHT is projected to increase by 30% and 36%, respectively.

Table 2. 2020 Base & 2040 No Action – Regional VMT & VHT

Model Output Metric	Base Year	2040 No Action	
		VMT / VHT	+/- vs Base Year
VMT	85,271,900	111,028,500	+25,756,600 (+30%)
VHT	2,403,200	3,260,900	+857,700 (+36%)

Source: DRCOG Focus Model, 2017

4. Level 1 Purpose and Need Screening

The DRCOG planning model was utilized to provide a high-level assessment of the regional significance of the Santa Fe Drive corridor under a range of corridor capacity scenarios. Model runs were completed for the following scenarios:

1. 2040 No Action, mix of arterial and expressway facility types **(2040 Base)**
2. 2040 Base scenario plus one additional lane on Santa Fe Drive **(2040+1Ln)**
3. 2040 Base scenario with Santa Fe Drive upgraded to an expressway facility type corridor-wide **(2040+Expwy)**
4. 2040 Base scenario with Santa Fe Drive upgraded to an interstate facility type corridor-wide **(2040+Interstate)**
5. 2040 Base scenario plus one additional lane on Santa Fe Drive AND upgraded to an interstate facility type corridor-wide **(2040+MaxCap)**

Regional model statistics were extracted as raw data for each scenario directly from the DRCOG model. Table 3 and Figure 2 illustrate the change in regional VMT, VHT, average speed, and vehicle hours of delay (VHD) for each of the Level 1 scenarios compared to the 2040 No Action (2040 Base) scenario.

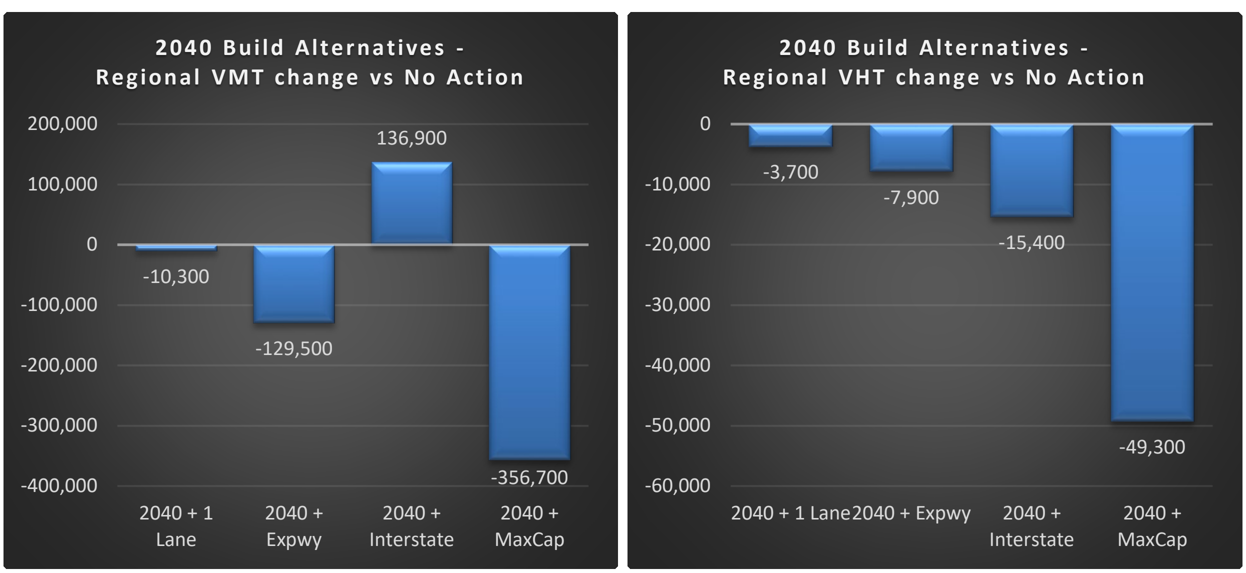
The scenario that adds a travel lane and retains the existing facility type (2040+1Ln) resulted in the smallest improvements to regional VMT, VHT, speed and VHD. Maintaining existing lanes and upgrading the facility to Expressway throughout (2040+Expwy) resulted in slightly greater declines in VHD and VHT than the 2040+1Ln scenario, and a much greater decline in VMT at just under 130,000 miles. The 2040 Interstate scenario is the only scenario that caused an increase in regional VMT at over 136,000 miles, though it does result in improvements to VHT, VHD, and speed. The 2040+MaxCap scenario with additional lanes and Interstate facility type resulted in the greatest decrease in regional VMT and VHT with a drop of nearly 370,000 miles and nearly 50,000 hours driving when compared to the 2040 No Action. This scenario also exhibits the greatest improvement in average speed by 0.4 miles per hour (MPH) and greatest reduction in vehicular delay at over 27,000 hours daily.

Table 3. 2040 Level 1 Build Scenarios – Metrics Compared to 2040 No Action

Regional Statistic Change	2040 + 1 Lane	2040 + Expwy	2040 + Interstate	2040 + MaxCap
VMT +/-	-10,300	-129,500	136,900	-356,700
VHT +/-	-3,700	-7,900	-15,400	-49,300
Speed (mph) +/-	0.0	0.0	+0.2	+0.4
VHD +/-	-2,990	-3,630	-7,360	-27,450

Source: DRCOG Focus Model, 2017

Figure 2. 2040 Level 1 Build Scenarios – Regional VMT & VHT Savings vs No Action



2040 daily traffic volume forecasts were developed for Santa Fe Drive, for the above-described Level 1 scenarios. The forecasted volumes were post-processed as described in the Traffic Analysis methodology above, and are illustrated in Table 4 and Figure 3.

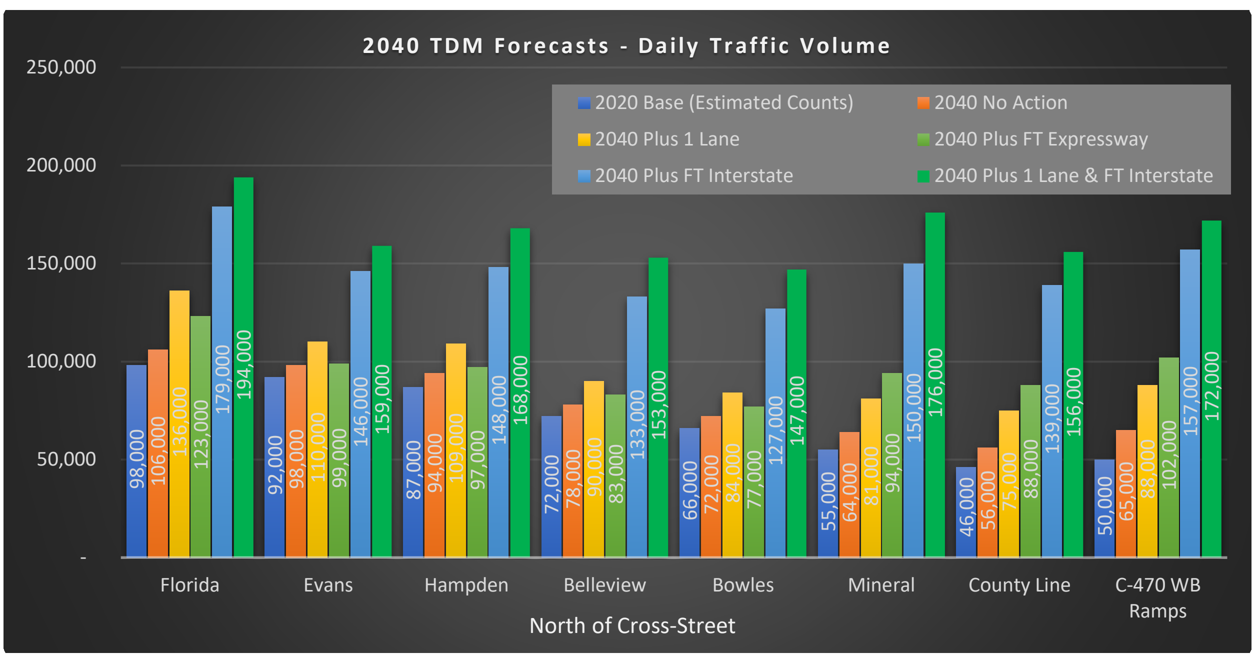
Comparing the 2020 Base to the 2040 No Action, daily traffic volumes are projected to grow between 7% and 39% along Santa Fe. Volumes are projected to increase by 7 to 9% north of Belleview (0.3% to 0.5% annually), 8% to 18% (0.5% to 0.8% annually) between Belleview and the southbound flyover ramp to EB C-470, and 18% to 39% (0.8% to 1.7% annually) south of the C-470 southbound flyover ramp.

Table 4. Santa Fe Drive Daily Traffic Volumes and Growth – Level 1 Screening

Santa Fe North of:	2020 Est. Counts	2040 No Action Volume	2020 to 2040 NA Growth		2040 + 1 Lane Volume	2040 NA to 2040 + 1 Lane		2040 + Expwy Volume	2040 NA to 2040 + Expwy		2040 + Intrst. Volume	2040 NA to 2040 + Intrst.		2040 Max Capacity Volume	2040 NA to 2040 Max Cap	
			+/-	%		+/-	%		+/-	%		+/-	%		+/-	%
Mississippi	98,000	107,000	9,000	9%	117,000	10,000	9%	108,000	1,000	1%	149,000	42,000	39%	157,000	50,000	47%
Florida	113,000	122,000	9,000	8%	136,000	14,000	11%	123,000	1,000	1%	179,000	57,000	47%	194,000	72,000	59%
Iowa	85,000	93,000	8,000	9%	102,000	9,000	10%	93,000	-	0%	132,000	39,000	42%	143,000	50,000	54%
Evans	92,000	98,000	6,000	7%	110,000	12,000	12%	99,000	1,000	1%	146,000	48,000	49%	159,000	61,000	62%
Dartmouth	89,000	97,000	8,000	9%	115,000	18,000	19%	99,000	2,000	2%	139,000	42,000	43%	164,000	67,000	69%
Hampden	87,000	94,000	7,000	8%	109,000	15,000	16%	97,000	3,000	3%	148,000	54,000	58%	168,000	74,000	79%
Oxford	77,000	84,000	7,000	9%	97,000	13,000	16%	87,000	3,000	4%	136,000	52,000	62%	155,000	71,000	85%
Belleview	72,000	78,000	6,000	8%	90,000	12,000	15%	83,000	5,000	6%	133,000	55,000	70%	153,000	75,000	96%
Prince	66,000	71,000	5,000	8%	88,000	17,000	24%	77,000	6,000	8%	122,000	51,000	71%	149,000	78,000	109%
Bowles	66,000	72,000	6,000	9%	84,000	12,000	17%	77,000	5,000	7%	127,000	55,000	77%	147,000	75,000	105%
Church	57,000	63,000	6,000	11%	79,000	16,000	25%	87,000	24,000	38%	137,000	74,000	118%	163,000	100,000	159%
Aspen Grove	55,000	63,000	8,000	15%	79,000	16,000	25%	88,000	25,000	40%	137,000	74,000	117%	162,000	99,000	157%
Mineral	55,000	64,000	9,000	16%	81,000	17,000	27%	94,000	30,000	47%	150,000	86,000	135%	176,000	112,000	176%
C-470 Flyover	51,000	60,000	9,000	18%	72,000	12,000	20%	79,000	19,000	32%	116,000	56,000	93%	131,000	71,000	118%
County Line	51,000	63,000	12,000	24%	75,000	12,000	19%	88,000	25,000	40%	139,000	76,000	121%	156,000	93,000	148%
C-470 WB Rmp	58,000	75,000	17,000	29%	88,000	13,000	17%	102,000	27,000	36%	157,000	82,000	109%	172,000	97,000	129%
C-470 EB Rmp	59,000	82,000	23,000	39%	88,000	6,000	7%	98,000	16,000	20%	132,000	50,000	61%	138,000	56,000	68%

Source: DRCOG Focus Model, 2017

Figure 3. Santa Fe Drive Daily Traffic Volume Forecasts – Level 1 Screening



Source: DRCOG Focus Model, 2017

The 2040 Action scenarios result in increased corridor traffic volumes compared to the 2040 No Action, with a wide range of volumes dependent upon the type of improvement:

- **2040 + 1 Lane** – This scenario results in relatively low growth in volumes compared to the 2040 No Action ranging from 6,000 to 17,000 additional daily vehicles (7% to 27%):
    - North of Bowles: 9,000 to 18,000 vehicles (9% to 24%)
    - South of Bowles: 6,000 to 17,000 vehicles (7% to 27%)
- **2040 + Expressway** – This scenario upgrades Santa Fe to an expressway from C-470 to Bowles. No improvements are included north of Bowles. The result is minimal growth in volumes north of Bowles while south of Bowles experiences volumes 20% to nearly 50% greater than the 2040 No Action:
    - North of Bowles: 0 to 6,000 additional vehicles (0% to 8%)
    - South of Bowles: 16,000 to 30,000 additional vehicles (20% to 47%)
- **2040 + Santa Fe Interstate** – This alternative upgrades Santa Fe to an interstate facility throughout the corridor (north of Bowles improves from an expressway while south of Bowles improves from a major arterial). The result is a large change in traffic volumes throughout the corridor.
    - North of Bowles: 39,000 to 55,000 additional vehicles (39% to 77%)
    - South of Bowles: 50,000 to 86,000 additional vehicles (61% to 135%)
- **2040 + Maximum Capacity** – This alternative upgrades Santa Fe to an interstate facility and adds a general purpose lane throughout the corridor. The result is traffic volumes of approximately 50% to 100% greater in the northern half of the corridor and volumes more than doubling in the southern half of the corridor.
    - North of Bowles: 50,000 to 78,000 additional vehicles (47% to 109)
    - South of Bowles: 56,000 to 112,000 additional vehicles (68% to 176%)

The travel demand results for these scenarios strongly suggest there is unmet demand that travels on alternate routes, traveling to alternate destinations, or not making the trip at all under the 2040 No Action alternative. Increased capacity through additional lanes and/or improved facility types results in substantial volume increases throughout the corridor, in particular to the south of Bowles.

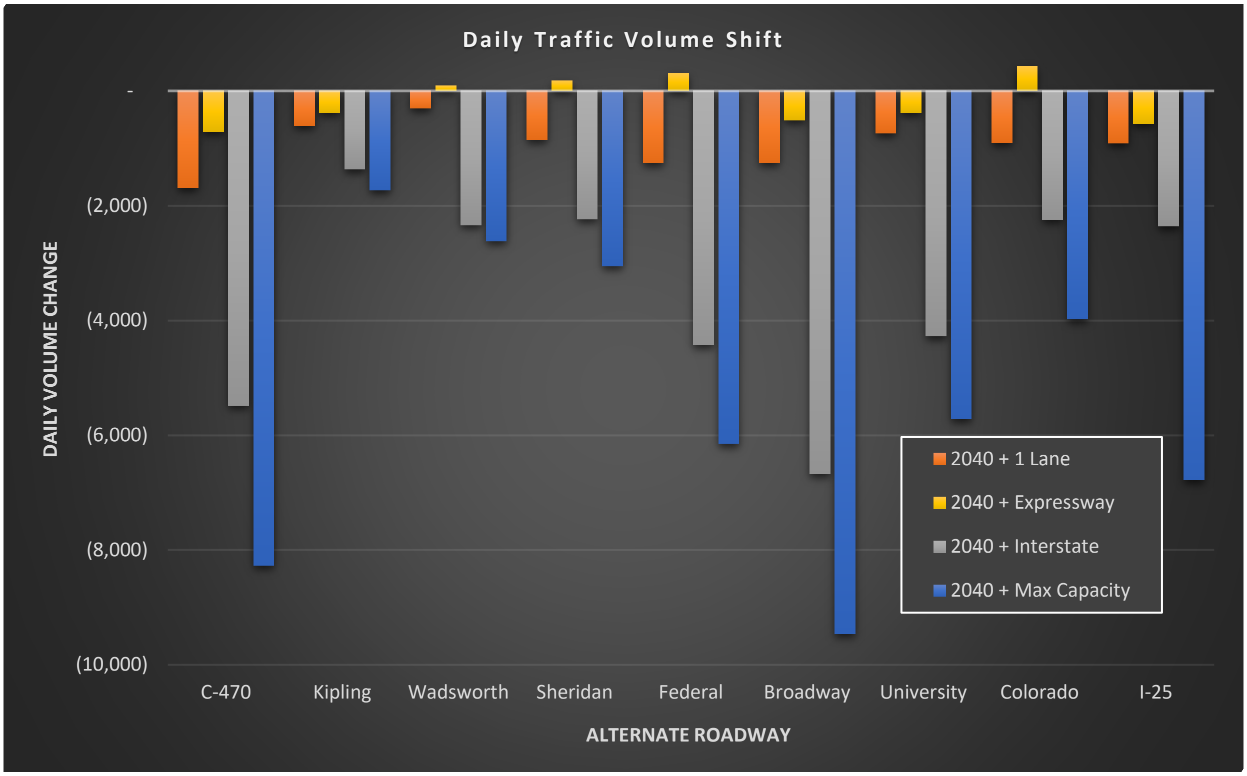
4.1 Screenline Analysis

A screenline analysis, assessing the effect on adjacent corridor travel, was performed for the Action Plan to better understand the effect that improvements to the Santa Fe corridor would have on travel patterns regionally. One screenline north of US 285 and one north of Aspen Grove considered major north-south arterials and highways from C-470 on the west to I-25 on the east. The analysis was based upon daily traffic volumes directly from the travel demand models; no post-processing was performed.

4.1.1 Screenline North of US 285

Figure 4 illustrates the shift in daily volumes on parallel facilities north of US 285 (Hampden Avenue) under each of the scenarios compared to the 2040 No Action model.

Figure 4. Screenline North of US 285 –Volumes vs 2040 No Action



Source: DRCOG Focus Model, 2017

Of the north-south arterials paralleling Santa Fe Drive, Broadway benefits the most from capacity improvements to the corridor, especially under the 2040 + Interstate and the 2040 + Max Capacity scenarios. Traffic volumes along Broadway are projected to decrease by as little as 1% in the 2040 + Expressway alternative and as much as 28% in the 2040 + Max Capacity alternative. Federal Boulevard and University Boulevard receive the next greatest benefit from an increased Santa Fe Drive capacity. Both see reductions in traffic volumes of up to about 15%.

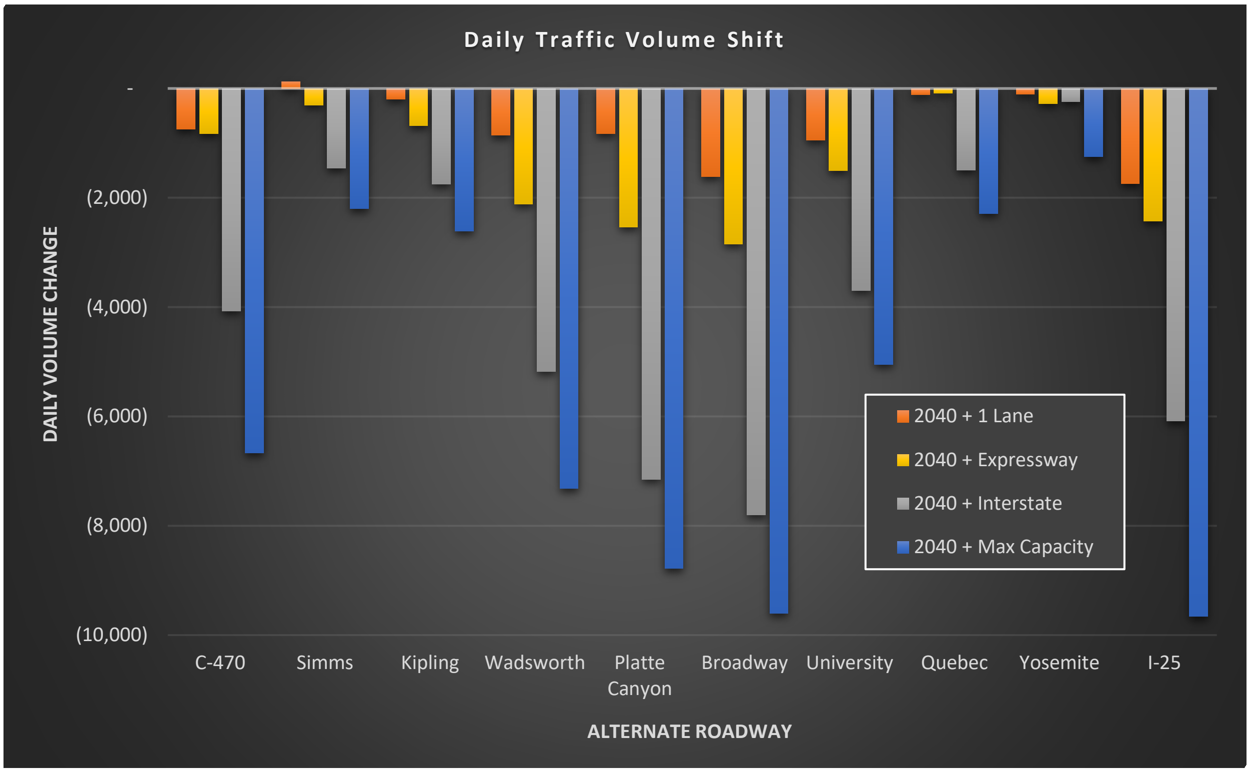
In addition to parallel arterials benefitting in the Build scenarios, both C-470 and I-25 see reductions in traffic volume. C-470 see reductions up to 7% while I-25 volumes decrease by up to 2%.

It should be noted that under the 2040 + Expressway scenario, several parallel routes actually increase slightly in volume north of US 285. This is likely due to improvements to Santa Fe Drive south of Bowles Avenue that result in greater volumes along Santa Fe Drive to the north. Because there are no improvements to Santa Fe Drive north of Bowles Avenue, the result is increased demand and displacement of traffic to these parallel routes.

4.1.2 Screenline North of Ken Caryl/Aspen Grove/Dry Creek

Figure 5 illustrates the shift in daily volumes on parallel facilities north of Ken Caryl Avenue, Aspen Grove, and Dry Creek Road under each of the Build scenarios compared to the 2040 No Action model.

Figure 5. Screenline North of Ken Caryl/Aspen Grove/Dry Creek – Volumes vs 2040 No Action



Source: DRCOG Focus Model, 2017

As with the screenline north of US 285, of the north-south parallel arterials, Broadway benefits the most from capacity improvements to Santa Fe Drive, especially under the 2040 + Santa Fe Interstate and the 2040 + Max Capacity scenarios. Traffic volumes along Broadway are projected to decrease between 4% and 22% depending on the scenario. Platte Canyon Road and Wadsworth Boulevard receive the next greatest benefit amongst parallel arterials. Platte Canyon Road, which has lower total volumes, sees a reduction of between 5% and 50% while Wadsworth Boulevard decreases between 2% and 14%, depending on the scenario.

Both C-470 and I-25 experience volume decreases under the Build scenarios, especially under the 2040 + Santa Fe Interstate and the 2040 + Max Capacity scenarios. C-470 see reductions up to 9% while I-25 volumes decrease by up to 4%.

5. Level 2A Screening Analysis

At Level 2A, options were screened for traffic conditions and crash reduction based on both qualitative and quantitative data. These screened options were refined from the Level 1 effort and categorized by Corridor Classification / Cross-Section, Spot Location Improvements, and

Intersection / Interchange Options. The complete list of options evaluated is provided in Appendix D of the Action Plan. Crash reduction estimates and methodology at Level 2A are provided in Attachment A to this report.

5.1 Roadway Elements – Corridor Classification / Cross-Section

Operational analysis of corridor-wide classification and cross-section options was completed using the DRCOG planning model, with new model runs performed for each Level 2A scenario. The regional model was adjusted from the base model for number of travel lanes and facility type on Santa Fe Drive to reflect each of the corridor-wide options. The Level 2A analysis took a similar yet more refined approach to that detailed above for the Level 1 screening. Model runs were completed for the following scenarios:

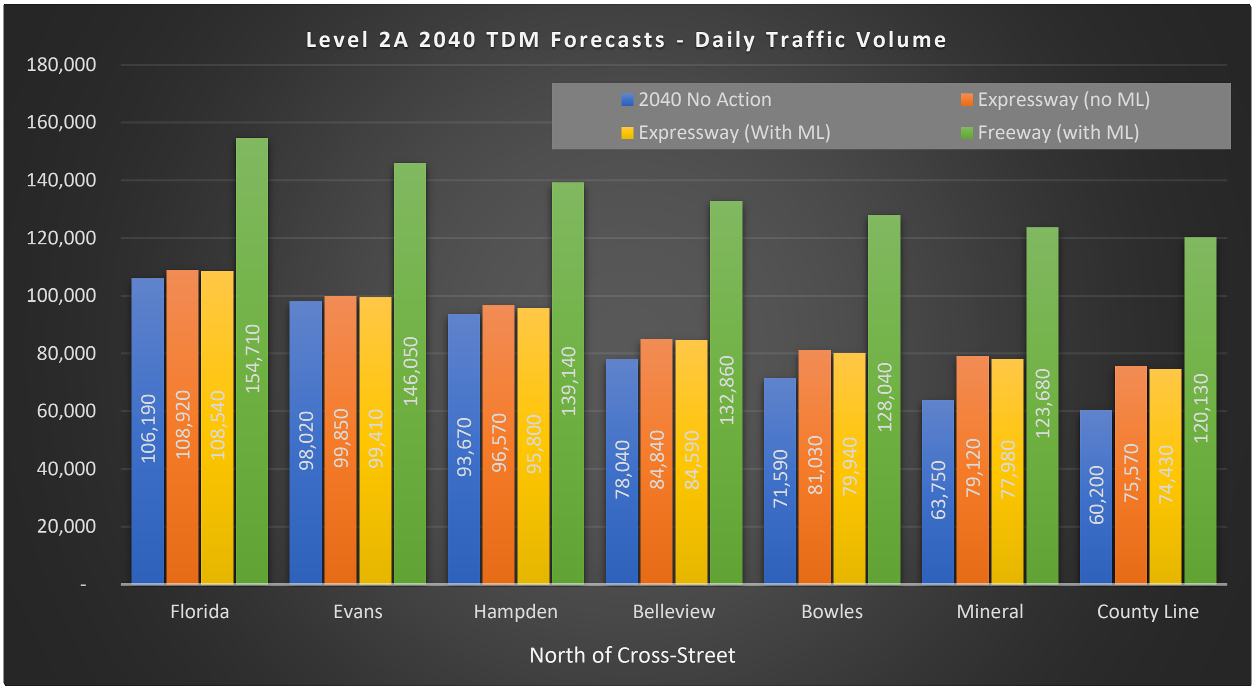
1. **R0 – 2040 No Action:** mix of arterial and expressway facility types
2. **R1 – 2040 Expressway:** conversion to expressway facility type with conversion of the existing high-occupancy vehicle (HOV) lanes to general purpose use
3. **R2 – 2040 Expressway, Managed Lane (ML) At-Grade:** conversion to expressway facility type with conversion of the existing HOV lanes to enhanced managed lanes
4. **R3 – 2040 Expressway, Managed Lane Grade-Separated:** conversion to expressway facility type with conversion of the existing HOV lanes to enhanced managed lanes with grade separation at intersections
5. **R4 – 2040 Freeway with Managed Lane:** conversion to interstate facility type with conversion of the existing HOV lanes to enhanced managed lanes

2040 daily traffic volume forecasts were developed for Santa Fe Drive, for the above-described Level 2A scenarios. The forecasted volumes were post-processed as described in the Traffic Analysis methodology above and are illustrated in Table 5 and Figure 6. Scenario R2 and R3 were modeled as a single 'expressway with managed lane' scenario due to the methods of the DRCOG planning model.

Table 5. Santa Fe Drive Daily Traffic Volumes – Level 2A Corridor/Cross-Section

Santa Fe North of:	2040 No Action	Expressway (no ML)	Change vs No Action +/-	Change vs No Action %	Expressway (With ML)	Change vs No Action +/-	Change vs No Action %	Freeway (with ML)	Change vs No Action +/-	Change vs No Action %
Mississippi	108,170	110,370	2,200	2%	110,330	2,160	2%	152,570	44,400	41%
Florida	106,190	108,920	2,730	3%	108,540	2,350	2%	154,710	48,520	46%
Iowa	103,470	105,640	2,170	2%	105,350	1,880	2%	149,000	45,530	44%
Evans	98,020	99,850	1,830	2%	99,410	1,390	1%	146,050	48,030	49%
Dartmouth	97,850	100,000	2,150	2%	99,300	1,450	1%	142,920	45,070	46%
Hampden	93,670	96,570	2,900	3%	95,800	2,130	2%	139,140	45,470	49%
Oxford	83,700	88,290	4,590	5%	87,460	3,760	4%	133,850	50,150	60%
Belleview	78,040	84,840	6,800	9%	84,590	6,550	8%	132,860	54,820	70%
Prince	71,000	79,730	8,730	12%	78,760	7,760	11%	126,590	55,590	78%
Bowles	71,590	81,030	9,440	13%	79,940	8,350	12%	128,040	56,450	79%
Church	62,960	78,330	15,370	24%	77,190	14,230	23%	122,890	59,930	95%
Mineral	63,750	79,120	15,370	24%	77,980	14,230	22%	123,680	59,930	94%
County Line	60,200	75,570	15,370	26%	74,430	14,230	24%	120,130	59,930	100%

Figure 6. Santa Fe Drive Daily Traffic Volume Forecasts – Level 2A Screening



Consistent with the Level 1 analysis, the 2040 Action scenarios at Level 2A result in increased corridor traffic volumes compared to the 2040 No Action, with a wide range of volumes dependent upon the type of improvement:

- **R1, Expressway without Managed Lane** – This scenario results in relatively low growth in volumes compared to the 2040 No Action ranging from 2,000 to 15,000 additional daily vehicles (2% to 26%)
- **R2 and R3, Expressway with Managed Lane** – Similar to scenario R1, the expressway with managed lane scenarios result in relatively low growth in volumes compared to the 2040 No Action ranging from 1,500 to 14,000 additional daily vehicles (1% to 24%)
- **R4, Freeway with Managed Lane** – This scenario upgrades Santa Fe to an interstate facility throughout the corridor. The result is a large change in traffic volumes from No Action ranging from 44,000 to 60,000 additional daily vehicles (50% to 100%).

The forecasted volume throughput summarized in Table 5 was utilized to estimate roadway capacity for each scenario. Approximate typical lane capacities by lane type were developed using the TRB publication NCHRP 825 planning guide to highway capacity and applied to the forecasted volumes to determine a volume-to-capacity (v/c) ratio that indicates a level of congestion that could be anticipated for each scenario. Additional qualitative criteria identified for the screening process included flexibility to variations on traffic volume. Average travel speed and assessment of the change in screenline traffic volume was obtained from the DRCOG planning model runs and used to assist in this determination of flexibility. Corridor scenario results are summarized in Table 6.

5.2 Intersections/Interchanges

Intersection and interchange options identified for screening at Level 2A were analyzed using the FHWA's Capacity Analysis for Planning of Junctions (Cap-X) Tool. The tool is used to evaluate a variety of intersection and interchange designs using the method of critical lane volume summation to provide capacity assessment at the planning level. Each location was assessed to maintain consistency in construction impacts and proposed footprint across each of the proposed options.

Results are presented in Table 7 with the analysis focused on the operations on Santa Fe Drive. An estimated v/c ratio was identified for the northbound and southbound movements, and a corresponding estimation of travel time reliability determined. Interchange options represent the greatest benefit to Santa Fe Drive traffic operations by removing signal delay from the corridor. At many locations alternative intersection configurations such as quadrant roads and continuous flow intersections (CFI) offer operational benefits to Santa Fe Drive traffic by reducing signal delay.

Table 6. Santa Fe Drive Corridor Analysis Results – Level 2A Screening

Corridor Location	NO ACTION (INCL HOV)						EXPRESSWAY – NO MANAGED LANE					
	Southbound			Northbound			Southbound			Northbound		
	Throughput (veh/day)	Daily V/C	PM Peak Hr V/C	Throughput (veh/day)	Daily V/C	AM Peak Hr V/C	Throughput (veh/day)	Daily V/C	PM Peak Hr V/C	Throughput (veh/day)	Daily V/C	AM Peak Hr V/C
North of Florida	52,750	1.03	1.27	53,440	1.04	1.24	55,070	1.01	1.24	53,850	0.98	1.17
North of Dartmouth	49,680	0.97	1.20	48,170	1.28	1.52	51,010	0.93	1.15	48,990	1.19	1.42
North of Belleview	39,470	1.05	1.30	38,570	1.03	1.22	43,170	1.05	1.30	41,670	1.02	1.21
South of Church	32,670	1.19	1.48	31,120	1.14	1.35	42,370	1.03	1.28	36,790	0.90	1.06
South of Mineral	31,790	0.77	0.96	28,410	1.04	1.23	41,230	1.00	1.24	34,080	0.83	0.99

Corridor Location	EXPRESSWAY – MANAGED LANE AT GRADE						EXPRESSWAY – MANAGED LANE GRADE SEPARATION					
	Southbound			Northbound			Southbound			Northbound		
	Throughput (veh/day)	Daily V/C	PM Peak Hr V/C	Throughput (veh/day)	Daily V/C	AM Peak Hr V/C	Throughput (veh/day)	Daily V/C	PM Peak Hr V/C	Throughput (veh/day)	Daily V/C	AM Peak Hr V/C
North of Florida	55,000	1.07	1.33	53,540	1.04	1.24	55,000	0.91	1.13	53,540	0.89	1.05
North of Dartmouth	50,650	0.99	1.22	48,650	1.29	1.54	50,650	0.84	1.04	48,650	0.81	0.96
North of Belleview	42,980	1.14	1.41	41,610	1.11	1.31	42,980	0.92	1.14	41,610	0.89	1.06
South of Church	41,560	1.10	1.37	36,460	0.97	1.15	41,560	0.89	1.10	36,460	0.78	0.93
South of Mineral	40,420	1.07	1.33	33,750	0.90	1.07	40,420	0.87	1.07	33,750	0.72	0.86

Corridor Location	FREEWAY WITH MANAGED LANE					
	Southbound			Northbound		
	Throughput (veh/day)	Daily V/C	PM Peak Hr V/C	Throughput (veh/day)	Daily V/C	AM Peak Hr V/C
North of Florida	80,440	0.83	1.03	74,270	0.77	0.91
North of Dartmouth	71,930	0.74	0.92	70,990	0.73	0.87
North of Belleview	64,980	0.92	1.13	67,880	0.96	1.14
South of Church	61,430	0.87	1.07	62,290	0.88	1.04
South of Mineral	52,190	0.74	0.91	52,070	0.73	0.87

		NO ACTION (INCL HOV)	EXPRESSWAY – NO MANAGED LANE	EXPRESSWAY – MANAGED LANE AT GRADE	EXPRESSWAY – MANAGED LANE GRADE SEPARATION	FREEWAY WITH MANAGED LANE
VMT	Santa Fe Corr	834,100	963,400	950,700	950,700	1,397,800
	Subarea	2,692,600	2,801,500	2,790,600	2,790,600	3,149,800
	Region	106,650,600	106,734,100	105,989,600	105,989,600	106,905,600
VHT	Santa Fe Corr	26,510	28,980	28,610	28,610	30,230
	Subarea	100,820	102,460	102,240	102,240	100,290
	Region	2,962,680	3,007,680	2,985,170	2,985,170	2,999,620
Avg Spd (mph)	Santa Fe Corr	31.5	33.2	33.2	33.2	46.2
	Subarea	26.7	27.3	27.3	27.3	31.4
	Region	36.0	35.5	35.5	35.5	35.6

SCREENLINES		NO ACTION – Parallel Roads	EXPRESSWAY NO ML – Parallel Roads			EXPRESSWAY ML AT GRADE – Parallel Roads			EXPRESSWAY ML GRADE SEPARATION – Parallel Roads			FREEWAY WITH ML – Parallel Roads		
		Daily Volume	Daily Volume	vs 2040 NA +/-	vs 2040 NA %	Daily Volume	vs 2040 NA +/-	vs 2040 NA %	Daily Volume	vs 2040 NA +/-	vs 2040 NA %	Daily Volume	vs 2040 NA +/-	vs 2040 NA %
Loc	North Half*	688,100	683,200	-4,900	-0.7%	678,900	-9,200	-1.3%	678,900	-9,200	-1.3%	654,400	-33,700	-4.9%
	South Half**	636,500	616,100	-20,400	-3.2%	612,200	-24,300	-3.8%	612,200	-24,300	-3.8%	591,900	-44,600	-7.0%
	South of Corr***	262,600	262,200	-400	-0.2%	261,100	-1,500	-0.6%	261,100	-1,500	-0.6%	263,700	1,100	0.4%

Screenlines: Parallel roads include C-470, I-25, and north-south arterials (mostly principal arterials) in between C-470 and I-25
* "North Half" Screenline: North of US 286
** "South Half" Screenline: North of Ken Caryl / Aspen Grove / Dry Creek
*** "South of Corr" Screenline: South of Trailmark / Highlands Ranch Pkwy / McArthur Ranch / Ridgegate
~average speed / speed limit x 1.1 for at-grade ML or 1.2 for grade-separated ML

Table 7. Santa Fe Drive Intersection/Interchange Analysis Results – Level 2A Screening

LOCATION	LEVEL 2A OPTION	SANTA FE OPERATIONS (V/C)	SANTA FE TRAVEL TIME RELIABILITY	NOTES AND ASSUMPTIONS
County Line Road	Signal Timing Modfications (NBL)	1.38	Low	Negligible change due to very low NBL demand
	No Action	1.38	Low	Note - WBR is limiting v/c
	SBL CFI	1.22	Low	Note - WBR is limiting v/c
	2x SB Left Turn Lanes	1.36	Low	Note - WBR is limiting v/c
Mineral Avenue	No Action	1.21	Low	
	Quad Road (SW or SW+NW)	0.89	Moderate	Analysis assumes extended SBR through main intersection (capacity improvement)
	SPUI Interchange	No Signal	High	
	Tight Diamond Interchange	No Signal	High	
Aspen Grove	No Action	0.86	Moderate	
	Channelized T	0.86	Moderate	Improves NB though only. Still presents delay for SB through traffic
	Channelized T, SB Grade Separated	0.27	High	
	NB Left CFI	0.83	Moderate	
Brewery Lane	No Action	0.83	Moderate	
	Channelized T	0.83	Moderate	Improves NB though only. Still presents delay for SB through traffic
	Channelized T, SB Grade Separated	0.10	High	
	NB Left CFI	0.80	Moderate	
Church Ave	No Action	0.84	High	Very low side street volumes
	Close West Leg, Chanelized T	0.82	High	
	Quad Road (SE)	0.76	High	
	Quad Road with Sumner St	0.76	High	
Bowles Ave	No Action	1.10	Low	
	EBL CFI	0.96	Low	
	NBL/SBL CFI	0.92	Moderate	
	Quad Road (NW)	0.85	Moderate	Analysis assumes extended NBL through main intersection (capacity improvement)
	Folded Diamond (West)	No Signal	High	No Signals on Santa Fe
Crestline	Close Access			Slight improvement on Santa Fe
	Improved RI/RO			Slight improvement on Santa Fe
Prince St	No Action	0.93	Low	
	Split Diamond w/ Belleview	No Signal	High	Assume similar to Belleview diamond
	RI/RO, No Signal	No Signal	High	
	Additional Lanes NB & EB/WB	0.85		
	Remove Lefts (via Belleview)	0.93	Low	
Belleview Ave	No Action	No Signal	High	No Signals on Santa Fe
	Add U-turns (close access Bellview to Union)	No Signal	High	No Signals on Santa Fe
	SPUI Interchange w/ Prince Connections	No Signal	High	No Signals on Santa Fe
	Diamond Interchange w/ Prince Connections	No Signal	High	No Signals on Santa Fe
Union St	No Action	1.06	Low	
	Channelized T	0.82	Moderate	Improves NB though only. Still presents delay for SB through traffic
	Channelized T, SB Grade Separated	0.17	High	No delay to NB or SB through raffic
Oxford Ave	No Action	1.26	Low	
	NBL/SBL CFI	0.90	Moderate	
	Quad Road (SW)	0.88	Moderate	Analysis assumes extended SBR through main intersection (capacity improvement)
	SPUI Interchange	No Signal	High	
	Tight Diamond Interchange	No Signal	High	No Signals on Santa Fe
Hampden Ave	No Action	1.38	Low	South intersection performs worst (1.38 v/c)
	Tight Diamond Interchange	No Signal	High	No Signals on Santa Fe
	SPUI Interchange	No Signal	High	No Signals on Santa Fe
	Folded Diamond (West)	No Signal	High	No Signals on Santa Fe
Dartmouth Ave	No Action	1.36	Low	With lanes per the cross-section alternative
	Additional NB/SB Lanes	0.86	Moderate	This is lanes ADDITIONAL to the cross-section designs
	Quad Road (SW+NW)	0.92	Moderate	Analysis assumes extended NBL through main intersection (capacity improvement)
	CFI	0.95	Moderate	
	SPUI Interchange	No Signal	High	
	Interchange *(Assume Tight Diamond)*	No Signal	High	No Signals on Santa Fe
Evans Ave	Interchange Reconstruction			Assume no change for traffic operations
Jewell Ave	Close Access			Slight improvement on Santa Fe
	Right-Out Only			Slight improvement on Santa Fe
	Right-In only			Slight improvement on Santa Fe
Iowa Ave	No Action	0.91	Low	
	Channelized T	0.73	Moderate	Improves SB though only. Still presents delay for NB through traffic
	Channelized T, NB Grade Separated	0.25	High	
Florida Ave	No Action	0.97	Low	
	Close East leg	0.90		
	Interchange (incl. Iowa Closure)	No Signal	High	
Mississippi Ave	No Action	1.11	Low	
	Quad Road (SW+NW)		Moderate	
	Diamond interchange	No Signal	High	
	SPUI Interchange	No Signal	High	

6. Level 2B Screening Analysis

Packaged corridor themes were developed for analysis at Level 2B that focused on solutions that can be implemented in the near term. The corridor themes generally consist of upgrades to the existing corridor cross-section by improving at-grade intersections, providing bottleneck reduction solutions, developing multimodal facility improvements, and access control. Many of these upgrades were analyzed independently as part of Level 2A above. Four themes were developed for screening, as described below.

1. **Theme 1: Corridor Safety and Operations Focus** – improvements that reduce conflicts and improve traffic flow
    - Auxiliary lanes
    - Intersections/interchanges providing highest capacity/least conflicts
    - Frontage road options and intersection closures to minimize direct access
    - New multimodal grade separations to reduce conflicts with Santa Fe crossings
    - Additional sidewalk, trail, and bicycle capacity
2. **Theme 2: Corridor Access Focus** – improvements that maintain access and improve operations for surrounding land use
    - Auxiliary lanes
    - Intersections/interchanges maintaining access
    - No new frontage roads or intersection closures
    - Multimodal improvements with minimal or no property impacts
3. **Theme 3: Multimodal Focus** – improvements that prioritize multimodal comfort, safety and opportunities
    - No new auxiliary lanes
    - Intersections/interchanges optimizing multimodal crossing
    - Frontage roads providing additional multimodal facilities
4. **Theme 4: Adaptability/Flexibility** – improvements that provide flexibility for potential future actions
    - add wider shoulders along Santa Fe Drive to improve safety and provide flexibility for future improvements/construction
    - Intersections/interchanges adaptable to future upgrades
    - Frontage roads providing additional area for traffic during future construction
    - Multimodal improvements without limiting future Santa Fe right-of-way modifications

Traffic operations analysis at Level 2B was completed using Trafficware's Synchro macroscopic analysis and optimization software. The software suits the primarily at-grade, signal controlled and coordinated corridor that is consistent across all Themes. 2040 forecasted daily traffic volumes developed during Level 2A analysis were applied at Level 2B, with the No Action and Expressway (with ML) volume sets presented in Table 5 applied to the No Action and Theme analysis respectively. Capacity analysis was conducted for both the AM and PM peak hours. Peak hour volumes were developed using the NCHRP 765 iterative methodology applied to the daily traffic forecasts developed at Level 2A.

Each theme was assessed for corridor-wide operational performance. A summary of the No Action and theme results is provided in Table 8. With a focus on traffic operations and safety, Theme 1 provides the greatest benefit to traffic operations and crash reduction. Theme 2, focusing on maintaining access, resulted in the least benefit to traffic operations and crash reduction:

- All Themes reduce travel time over the No Action. Travel time is lowest for Theme 1 and highest for Theme 2
- All Themes reduce vehicular delay over the No Action. Delay reduction is largest under Theme 1 and lowest under Theme 2. Theme 1 can accommodate the greatest increase in traffic volume over the No Action while maintaining the same travel speed
- Throughput increases under all themes compared to the No Action
- The greatest crash reduction is recognized under Theme 1 and Theme 4

Table 8. Level 2B Screening Corridor Results, No Action and Themes

		CORRIDOR RESULTS - TRAFFIC OPERATIONS				
		No Action	*Safety/Ops*	*Access*	*Multimodal*	*Adapt/Flex*
		NA	T1	T2	T3	T4
Total Travel Time VHT (hr)	AM PEAK PERIOD	2370	1760	2130	1870	1820
Total Miles VMT (mi)	AM PEAK PERIOD	53100	57100	58100	57250	57350
Average Corridor Speed (mph)	AM PEAK PERIOD	22	32	27	31	31
NB Corridor LOS	AM PEAK PERIOD	E	C	D	C	D
SB Corridor LOS	AM PEAK PERIOD	C	B	C	B	C
Flexibility*	AM PEAK PERIOD	-	+16%	+9%	+10%	+11%
Total Travel Time VHT (hr)	PM PEAK PERIOD	2760	1910	2610	2290	2240
Total Miles VMT (mi)	PM PEAK PERIOD	54700	59050	59250	59300	58450
Average Corridor Speed (mph)	PM PEAK PERIOD	20	31	22	26	26
NB Corridor LOS	PM PEAK PERIOD	C	B	B	B	B
SB Corridor LOS	PM PEAK PERIOD	E	C	E	D	D
Flexibility*	PM PEAK PERIOD	-	+11%	+2%	+5%	+4%

*Capacity available before reaching No Action speeds

	CORRIDOR RESULTS - TRAFFIC SAFETY				
	No Action	*Safety/Ops*	*Access*	*Multimodal*	*Adapt/Flex*
	NA	T1	T2	T3	T4
Crashes per MVMT**	2.94	2.86	2.90	2.87	2.86
Percent Change in Rate vs Existing	1.6%	-1.2%	-0.1%	-1.0%	-1.3%

**Million Vehicle Miles Traveled

7. HOV Lane Evaluation

An HOV Lane Evaluation White Paper is provided as Attachment A. The paper evaluates alternatives for the HOV lane that currently exists on Santa Fe Drive between Bowles Avenue and I-25. The alternatives evaluated are illustrated in Figure 1 of the paper and comprise:

1. Maintain as existing with design and/or operational adjustments
2. Conversion to a general-purpose lane
3. Relocate the HOV from the existing left lane to the right lane
4. Enhanced at-grade managed lanes
5. Enhanced managed lanes including grade separation at major intersections

The paper provides a discussion of safety, cost, operations, legal barriers and construction for each alternative. There are benefits and drawbacks to each alternative and ultimately any proposed action is likely to be driven by state policy. A generalized comparison of characteristics for each of the five alternatives is provided in Table 11 of the paper.

8. ITS/Technology Evaluation

An ITS and Transportation Technology Evaluation White Paper is provided as Attachment B. The paper highlights the technologies that are currently operational on the Santa Fe Drive corridor and details a range of potential ITS and technology-based strategies that could be further implemented on the corridor. The following strategies are discussed and assessed for practicality, compatibility, and cost:

- Traffic Operations Center (TOC)
- Enhanced Communications Infrastructure
- Incident Management Plans
- Traveler Information (Variable Message Signs)
- Queue Warning Systems
- Variable Speed Limit Systems
- Enhanced Pedestrian Detection

Many of these strategies can be implemented with minimal disruption to traffic, within existing right-of-way, and over a relatively short timeframe. These strategies are also highly flexible with individual or blended implementation possible depending on need and funding. A complete summary of each technology and their benefits is provided in Attachment B.

9. References

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Attachment A. HOV LANE EVALUATION WHITE PAPER

Santa Fe PEL
C-470 to I-25

HOV LANE EVALUATION WHITE PAPER

October 12, 2021

Purpose

This paper evaluates potential alternatives to improve operations of the current high-occupancy-vehicle (HOV) lane configuration on Santa Fe Drive between C-470 and I-25. Empirical evidence of the impacts of managed lane implementation in Colorado and a discussion on the impacts of other HOV projects across the nation, their solutions to HOV lanes that are not meeting goals, and design strategies to improve the corridor are presented. Each section follows up with a discussion on how these factors apply to each alternative on Santa Fe Drive. Finally, this evidence will be applied by offering recommendations on how the current HOV lane issues could be improved and the pros and cons of each presented alternative in this wider context.

Introduction

Santa Fe Drive runs north-south between C-470 and I-25 between Denver and Littleton. It currently operates as an urban principal arterial and is heavily trafficked. The roadway is owned by the Colorado Department of Transportation (CDOT); traffic signals and ITS technologies along the corridor are operated and maintained by CDOT, the City of Denver, and the City of Littleton. A HOV lane runs along much of the corridor's length between Platte River Drive and Bowles Ave in the southbound direction and between Bowles Ave and Alameda Ave in the northbound direction. The HOV Lanes, constructed in 1995, were originally intended for bus transit and carpools, however, the introduction of light rail parallel to Santa Fe Drive in the year 2000 diverted trips from the Bus/HOV lanes to light rail [1]. Currently vehicles with occupancy of 2+, motorcycles, and left turning vehicles are allowed access between 6:00AM and 8:30AM in the northbound direction and between 4:00PM and 6:30PM in the southbound direction. However, growing congestion in the general-purpose lanes during peak hours when HOV restrictions are in place, low utilization of the HOV lane, and high violation rates have raised questions as to how to improve operations along the corridor.

Alternatives

Santa Fe Drive has several unique features that should be considered when determining and presenting potential alternatives to the current HOV lane configuration. For example, Santa Fe Drive has at-grade signalized intersections along the corridor that all lanes, including HOV lanes, must pass through. Many HOV examples across the nation are constructed on unsignalized freeways which allow for more flexible solutions when trying to improve the facilities. Left turns at signalized intersections on Santa Fe Drive requires drivers to cross through the HOV lanes to access their intended movement. This presents issues for drivers who might expect less conflict in an HOV lane. This also makes violation enforcement difficult as officers must determine if the driver is illegally accessing the HOV lane or crossing over for a left turn. Currently, there are no specified locations for police enforcement [1]. A light-rail system with several stops and access points runs next to much of Santa Fe Drive, which may impact driver decisions on carpooling and any future transit use of the HOV lanes. The alternatives presented in this paper take into consideration these unique and specific features of Santa Fe Drive. To help relieve congestion along the mainline and improve utilization of the HOV lane, five alternatives are presented and evaluated in this paper. These alternatives are summarized in **Table 1** and visual representation can be found in **Figure 1**. Each alternative's recommended operational adjustments, design, and analysis is expanded upon throughout the paper.

Table 1 – Summary of Alternatives

Alternative Number	Lane Type	Description	Highlights
1	HOV	Maintaining the HOV lane with design/operational adjustments to improve operations and safety	Lowest cost while still improving operations and safety; no ability to dynamically manage demand
2	GP	Conversion of existing HOV lane to a general-purpose lane	Removes the need for enforcement and provides improved traffic operations and safety; requires legislation; no ability to dynamically manage demand
3	HOV	Relocation of the HOV lane from the left lane to the right lane	Reduces left turn weaving conflicts; improves ability to enforce HOV lane; no ability to dynamically manage demand
4	HOT	Enhanced at-grade managed lanes from C-470 to I-25	Ability to dynamically manage demand and collect toll revenue; paying users still experience delay at signalized intersections
5	HOT	Enhanced managed lanes from C-470 to I-25 including grade separation at major intersections	Ability to dynamically manage demand and collect toll revenue; costly with grade separations for HOT lane

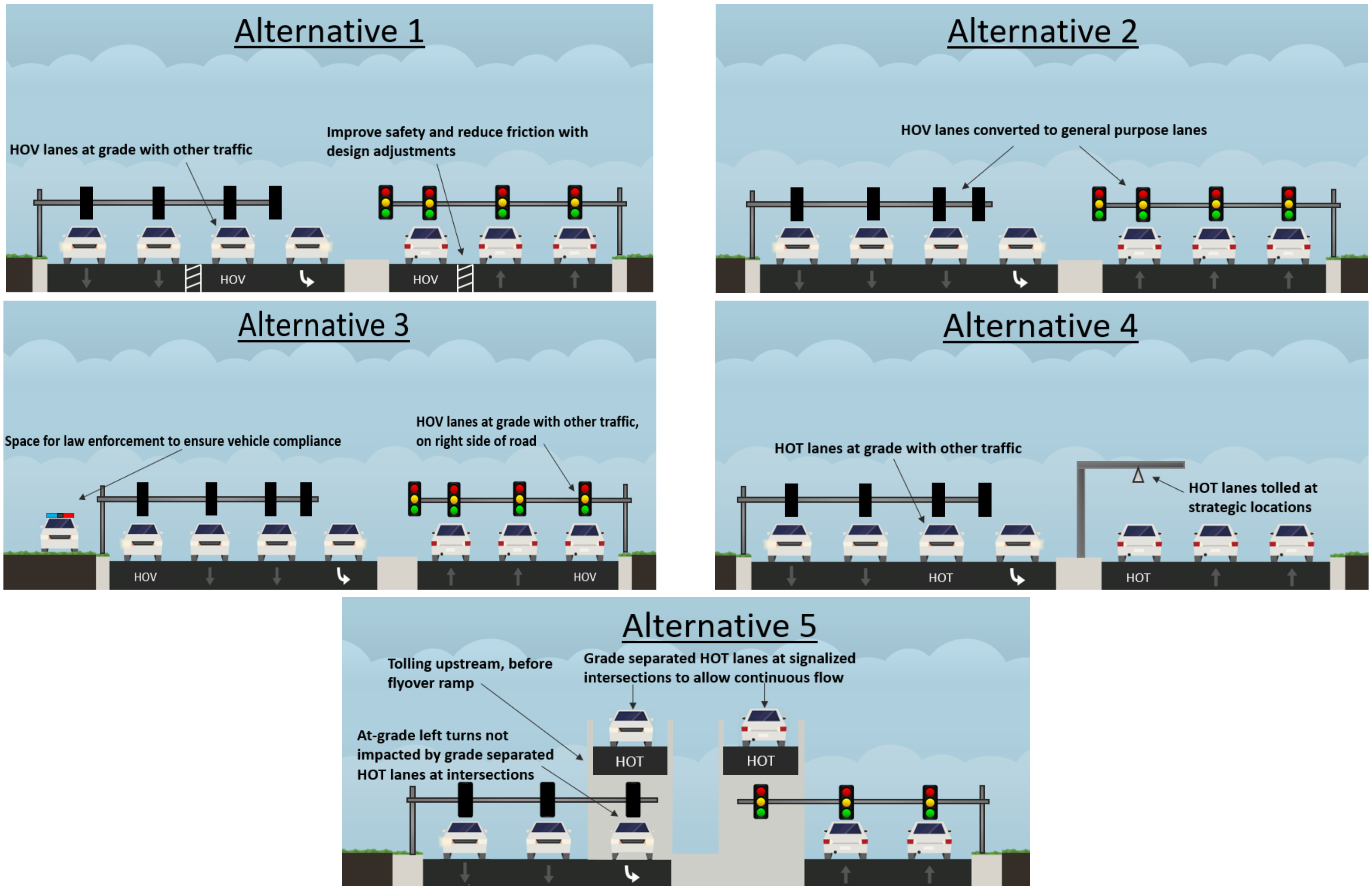

Figure 1. Alternative Cross-Section Examples

National Strategies and Examples

The alternatives presented above address, to varying degrees, the different features of Santa Fe Drive and how they might affect performance along the corridor. To make an informed decision on the feasibility and benefits of each alternative, the scenarios must be scrutinized and analyzed using available tools, common strategies, and past experiences from other agencies. There have been a number of successful HOV and managed lane projects and initiatives across the country. Many of these successful cases went through several changes and improvements to achieve the desired goals and objectives. Typically, the purposes of making changes to existing HOV corridors was to improve performance and address political and public interests [2]. Common strategies have included adjusting and implementing pricing, modifying occupancy requirements, changing hours of operation, moving access points, updating vehicle types that can access the HOV facilities, and the conversion of HOV lanes to GP lanes [2]. In a survey study conducted in 2008 by FHWA, the most common improvement considered by agencies for HOV performance was conversion to HOT lanes and adjusting pricing, while the most implemented improvements included access changes and vehicle eligibility [2]. Looking at specific examples can provide a basis for selecting the appropriate alternative to improve the underutilized HOV lanes on Santa Fe Drive. Presented below is a summary of strategies to improve HOV operations and examples that have been deployed across the United States of America.

Access Points (Ingress/Egress)

The existing HOV lanes along Santa Fe Drive utilize continuous access points with a solid white painted line, allowing drivers the option to enter the HOV lane at any point along the corridor. With any of the HOV or HOT lane alternatives, consideration may be given to adjusting access along the corridor. Appropriate placement of managed lane ingress and egress points is important to ensure adequate access for vehicles entering and exiting the facility and discouraging weaving and illegal lane entry. A study found that when ingress points are placed too near a corridor access point, excessive weaving is often observed where motorists attempt to quickly cross multiple lanes of traffic to reach the ingress [3]. Similar actions are often observed in reverse for motorists leaving the facility if the egress is too close to an exit. Such maneuvers not only increase the risk of crashes, but can also result in significant capacity reduction of general-purpose lanes because through traffic is slowed by the weaving vehicles [4].

The FHWA recommends 600 to 800 feet of length for ingress and egress zones, while California recommends a minimum of 800 feet. CDOT has generally used a distance of 750 to 800 feet on recent projects [5]. Based on this precedent, it is recommended that ingress and egress zones be a minimum of 750 feet in length. One study found greater lane compliance associated with longer access zones [3], suggesting that where possible it may be beneficial to consider increased ingress and egress lengths. Another 2009 study had found that continuous access can result in fewer accidents, injuries, and fatalities [6]. Locating hotspots for crashes associated with the ingress and egress locations of the HOV lane could help in determining the appropriate strategy.

Alternative 4 and Alternative 5 would likely need consideration for access points. Tolling, access points, and access type would need to be strategically placed to allow enough space and time for vehicles entering Santa Fe Drive to cross all other lanes to enter the HOT lane. Alternative 4 would need to provide proper access points for HOV lanes to enter and exit while still accommodating vehicles crossing over to make left turns at intersections. Many arterial HOV examples have continuous access and could be a consideration for Alternative 1 and Alternative 3.

Occupancy Requirements

Currently Santa Fe Drive allows vehicles with occupants of 2+ to access the HOV lanes. One strategy to improve HOV lanes is modifying types of vehicles and occupancy requirements. This strategy has been used nationally to address HOV lane utilization and when upgrading HOV lanes to high occupancy toll (HOT) lanes. Implementing tolling on managed lanes allows single occupant vehicles and others to access less congested segments of a corridor, increasing utilization of the managed lane, decreasing travel times for paying customers, and removing vehicles from more congested areas.

A 2014 panel survey of HOV and HOT users on I-85 in Atlanta evaluated the impacts of occupancy requirement changes [7]. The original 2+ occupancy HOV lanes on I-85 were changed to 3+ occupancy HOT lanes. Usage of the HOT lanes nearly doubled compared to HOV usage for those participating in the survey; this was largely driven by solo drivers paying the toll to access the lane (12% share of HOV trips to 82.2% share of HOT trips) [7]. In fact, the survey found a decrease in 2-person vehicles using the HOT lane, which had shifted to the general-purpose lane [7]. In another study, changes due to occupancy requirements from 3+ to 2+ on the El Monte Busway in Los Angeles County were evaluated [8]. In 1999, legislation required the reduction in occupancy requirements. It was found that dropping the occupancy had damaging effects on speed and travel times in both the HOV lanes and general-purpose lanes; occupancy was subsequently increased to the original 3+ requirement for peak hours in 2000 [8]. It should be noted that this corridor was later converted into a HOT lane in 2014 allowing 3+ to drive for free and 2+ to drive for free on off peak hours [9]. The Katy Freeway in Houston went through several iterations of occupancy HOV requirements from 1984 to 1987. Originally only allowing buses and authorized vehicles, the requirements dropped from 4+ to 2+ until 2009 when the Katy Freeway included fully managed HOT lanes [10].

ELECTRIC VEHICLE AND ALTERNATIVE FUEL EXEMPTIONS

In addition to occupancy requirements, there are specific vehicle exemptions that can be used to increase utilization of a HOV lane. These include access by single occupant vehicles paying a toll (discussed in other sections), motorcycles, and low emissions and energy efficient vehicles (LEEEVs). The passing of the Fixing America's Surface Transportation (FAST) Act in 2015 added alternative fuel and electric vehicles to the list of vehicle exemptions under US Title 23 Code 166 (b)(5). Eventually legislation required certain LEEEVs to pay a toll (further legislative discussion occurs in a separate section) [11]. Colorado, under 1 CCR 204-28, had allowed hybrid and low emission vehicles the option to access express lane facilities without paying a toll. The program had handed out limited passes to ensure the additional vehicles accessing the lanes did not negatively impact operations. The program ended in May 2020 due to US Title 23 Code 166 (b)(5)(B)'s expiration in 2019 for LEEEV exemptions [12]. Alternative fuel and electric vehicle toll exemptions expire in 2025 unless Congressional action extends the program. HB19-1199 was introduced in the Colorado General Assembly in February of 2019 to offer electric vehicles the opportunity to register to access express lanes without paying a toll [13]. It seems that the bill was not passed, and the bill postponed indefinitely. As of now, there are no known exemptions in Colorado for single occupant electric or alternative fuel vehicles to access HOV/HOT lanes without paying a fee.

Other recent developments in Colorado legislation may impact considerations for electric vehicle exemptions for tolling on HOV lanes. 2 CCR 601-22 will require CDOT and MPOs to consider greenhouse gas (GHGs) emissions and to maintain certain thresholds when planning and constructing new transportation projects [14] [15]. Allowing electric vehicles free access to express lanes is sometimes encouragement for purchasing exempt vehicles [16] [17]. In addition, if congestion can be mitigated by giving HOV lane access to more vehicles, there may be additional air quality benefits.

Santa Fe Drive currently has a 2+ occupancy requirement, and therefore utilization is unlikely to improve by changing occupancy. Opening these lanes to single-occupancy vehicles willing to pay could improve utilization under Alternative 4 and Alternative 5. However, having motorists pay for a lane that is already underutilized by any occupancy levels may not draw public support. Alternative 5 may offer a solution to this dilemma. By providing lanes that can bypass intersections, it would offer a clear additional benefit (bypassing signals) that motorists may find more appealing to pay for. Care may need to be taken in managing tolling, however, to avoid excessive use of the lane that may lead to increased congestion in the HOV lane. Maintaining specific speeds is a requirement for conversion of HOV to HOT lanes (legal implications are discussed in a later section). Alternative 1 and Alternative 3 could see increased utilization if electric vehicles are allowed access to the HOV lanes without implementing tolling facilities and keeping the HOV lane designation. In addition, if studies are conducted on GHG benefits of allowing toll-free access for these vehicles, it could help meet the requirements of 2 CCR 601-22. However, conditions would need to be monitored on the corridor to ensure the number of drivers does not impact speed and operations of the HOV lane. It should be noted that the previously existing hybrid electric vehicle program allowing access to HOV lanes for free had only recently ended, and that using a similar program on alternative fuel and electric vehicles may still meet federal and state requirements.

Managed Lane Design Features

Research shows that the design of managed lane elements has a direct impact on the operations and safety of the whole facility. This section discusses critical design elements including recommendations for ideal widths and characteristics to produce the highest quality facility. The roadway design process would require a full review of the available ROW and available space to determine how the facility could be designed. These recommendations should be incorporated into that process to optimize operations and safety of the facility and can be applied to the majority of the alternatives presented.

LANE WIDTH AND LEFT SHOULDER WIDTH

Lane width and left shoulder width have a large impact on the safety and operations of freeway managed lanes. A 2015 study of freeways in Texas found that 12-foot lanes had travel speeds approximately 2.2 mph higher on average than 11-foot lanes, and had between 5% and 11% fewer crashes (depending on the overall number of freeway lanes). The study also found a reduction in crashes of roughly 6% per additional foot of left shoulder width [18]. These findings and their general applicability to managed lanes have been corroborated by several additional studies [19] [18]. Adding travel lanes has also been shown to result in a reduction in crashes, but these benefits tend to be offset if lane width and shoulder width must be reduced to allow space for the new lane [19]. A 2009 study found that higher shoulder width and overall HOV lane width resulted in lower crash rates [6]. Managed lane and HOV guidelines often cite 12-foot lanes and 10-foot to 14-foot wide shoulders as the preferable amount of space for both motorists and for police enforcement [20]. Based on these findings, it is recommended that a managed lane solution have a 12-foot width, and a full sized 12-foot left shoulder be employed wherever possible. Providing adequate lane and shoulder width for Alternative 5 could be considered, particularly due to the reconstruction and reconfiguration required to build the fly over ramps. Widening of Santa Fe Drive is also a potential improvement to each of the alternatives presented in this paper and may provide safety and operational benefits.

LANE SEPARATION TYPE

Managed lane separation type is also an important consideration. On roadways where a large speed differential between general-purpose and managed lanes is likely to exist, more restrictive separation types are typically recommended to reduce unsafe weaving between the lanes [21]. That said, many experts discourage the use of concrete barriers on managed lanes without grade separation due to the possibility of high-speed barrier impacts. If concrete barriers are used on single-lane facilities, a minimum barrier-to-barrier clear width of at least 18 feet is recommended [22]. Pylons are also an effective option to restrict unwanted weaving. They require less right-of-way to install than barrier, can be impacted by vehicles without causing significant risk of injury, and can be traversed by first responders in the event of an emergency. Many agencies see pylons as an undesirable option though due to their large ongoing maintenance requirements and associated cost [23] [24]. Furthermore, both barriers and pylons can impede snow removal, and pylons can be damaged by plows and accumulation of snow. For this reason, these options are less desirable in regions such as Colorado that experience high snowfall totals.

Perhaps the most common separation type between managed lanes and general-purpose lanes is a striped buffer. This separation type can be easily crossed in the event of an emergency, it doesn't create a risk to drivers from impacting a stationary object, and it doesn't pose the same difficulties related to snow removal as more restrictive treatments. The drawback is that buffers are much more susceptible to "friction effects" when a speed differential exists between managed and general-purpose lanes, and to illegal lane changes and collisions from unexpected weaving. In addition, buffers wider than 4-feet tend to collect debris, which presents safety and maintenance issues [25]. Multiple studies of buffer separated facilities in the United States have found that the width of buffer used is a significant factor in reducing crash rates. **Figure 2** depicts the results of one such study that found increased buffer widths correlated to fewer crashes and increased corridor safety[1]. As it stands, it may be possible to add a small striped buffer to Alternative 1 or Alternative 3 by removing shoulder width (although consideration should be given to safety impacts from shoulder width) or restriping of the roadway. This could also be achieved by slightly widening the roadway. This could offer drivers a higher sense of safety and security. Alternative 5 could make use of reconstruction and potential widening to ensure adequate buffer space between the HOV lane and general-purpose lanes. If improved travel times and speeds are an expected outcome, a buffer zone could greatly benefit these alternatives.

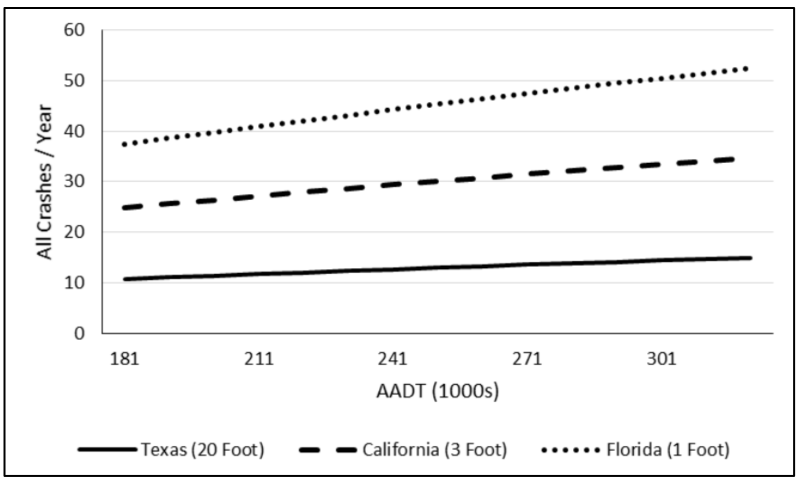

Figure 2. Total Crashes for Varying Buffer Widths on 10-lane Freeways with HOT Lanes [23]

Given the variety of interconnected factors involved, a separation treatment should be chosen based on the unique conditions on the corridor. **Table 2** outlines some key safety considerations

[1] Each of the buffer widths were found in different states, but the authors of the study found that there were no significant systemic differences that would render the comparison invalid.

associated with different separation treatments and can help assess applicability of different treatments to a particular scenario.

Table 2 - Safety Issues Associated with Managed Lane Separation Types [23]

Potential Safety Issue	Barrier Separation	Buffer Separation	Striping
Excessive Speeding	X		
Increased crash frequency at ingress/egress locations	X	X	X
Increased crash severity at ingress/egress locations	X		
Illegal lane-weaving		X	X
Speed differential crashes	X	X	X
Incident management accessibility	X		
Debris collection on buffer area	X	X	
Inclement weather (snow, flooding, etc.)	X	X	

Table 3 summarizes the most important considerations identified for the selection of lane separation treatments. The majority of these separation treatments can be found on existing Colorado managed lanes. Concrete barrier can be found on the I-25 reversible lanes near downtown Denver; a wide buffer can be found on C-470 and US-36; narrow buffer can be found on I-25 north of Denver; and a striped separation can be found on the I-70 Mountain Express lanes. A combination of separation treatments may also be warranted to account for unique conditions at different locations on a corridor. For example, the Central 70 corridor (I-70) [under construction] has a default of four-foot buffers in most locations, but it has two foot and striped buffers in some locations near termini of the managed lanes where space is significantly limited.

Table 3 - Summary of Relative Strengths of Lane Separation Treatments

Category	Consideration	Concrete Barrier	Delineators	Buffer (3'+)	Buffer (1-2')	Striped
Safety	Crash frequency	5	4	3	2	1
	Severe crashes from barrier impact	1	4	5	5	5
	Emergency Access	1	3	5	5	5
Operations	Illegal lane weaving	5	4	3	1	1
	Friction effects from adjacent lanes	5	4	2	1	1
	Relative free-flow speed	5	4	4	4	5
Cost	Construction cost	1	3	5	5	5
	Ongoing maintenance cost	3	1	5	5	5
	Right-of-way requirement	1	3	3	4	5

**Scored on a scale of 1 to 5, with 1 being least desirable and 5 being the most desirable*

Given the added safety associated with wider buffers, and the snow removal difficulties associated with barrier and delineators, a wide buffer (minimum three-foot) is likely the best separation treatment for most of the identified alternatives – with the exception of Alternative 5, which would require some concrete barrier for flyover ramps and the associated transitions. The pros and cons of the different lane separation treatments noted in this section are summarized in **Table 4**.

Table 4 - Pros and Cons of Different Managed Lane Separation Treatments

	Pros	Cons
Concrete Barrier	• Ensures compliance to designated ingress/egress zones (eliminates illegal lane weaving) • No friction effects from adjacent GP lanes	• High initial cost • Increased potential for severe crashes from barrier impacts • Requires wide barrier-to-barrier clear width • Limited emergency access • Potential for debris to collect along the barrier • Accumulation of snow/ice along the barrier during inclement weather
Delineators	• Ensures compliance to designated ingress/egress zones (eliminates illegal lane weaving) • Reduced risk of accidents from vehicular impacts compared to barrier • Lower friction effects from adjacent GP lanes compared to buffer/striped separation • Less installation width and right-of-way required compared to concrete barrier	• High ongoing maintenance requirements and costs • Potential for impacted posts to become removed and land on the roadway • Potential for debris to collect along the posts • Accumulation of snow/ice along the barrier during inclement weather and the potential for posts to be damaged by snow plows
Buffer (3'+)	• Low construction cost • Low ongoing maintenance cost • Easy access for emergency personnel • Increased safety compared to striped and narrow buffers	• High crash frequency compared to more restrictive treatments • Low compliance to designated ingress/egress zones (illegal lane weaving) compared to more restrictive treatments • More right-of-way required compared to narrow and striped buffers
Buffer (1-2')	• Low construction cost • Low ongoing maintenance cost • Minimal right-of-way required • Easy access for emergency personnel	• High crash frequency compared to wider buffer and more restrictive treatments • High friction effects from adjacent GP lanes compared to wider buffers and more restrictive treatments • Low compliance to designated ingress/egress zones (illegal lane weaving) compared to wider buffer and more restrictive treatments
Striped	• Lowest cost • Least right-of-way required • Easy access for emergency personnel	• Highest crash frequency • Highest friction effects from adjacent GP lanes • Lowest compliance to designated ingress/egress zones (illegal lane weaving)

GRADE SEPARATION

Alternatives 5 involves some form of grade separation of traffic on Santa Fe Drive from cross-traffic at intersections. It would involve grade separated flyover ramps for managed lanes at key intersections. This is a new concept for managed lanes and is precipitated by the need to improve operations on an expressway facility with at-grade intersections. CDOT's Express Lane Master Plan developed a high-level operational concept for such a facility along Santa Fe Drive, including a list of intersections where flyover ramps might be deployed [26]. The reduction of signalized intersections encountered by the managed lanes would increase lane capacity and potentially improve safety, while also increasing appeal of the lanes to the travelling public.

It should be noted that the Express Lane Master Plan (ELMP) evaluated operations at a high level for a grade separated express lane scenario. The model results were problematic as they resulted in extremely high revenues in the express lanes, but untenable congestion conditions in the adjacent general-purpose lanes. Based on recent SH 119 modeling efforts, it is believed that this issue was likely due to queuing as vehicles tried to enter the express lane which was so heavily utilized that proper gaps could not be provided for ingress. However, these observations are not likely to reflect conditions on such a facility as capacity and access to the express lanes would be controlled via adjustments in pricing. If the grade separation is desired to move forward, more detailed microsimulation analysis should be performed to better understand potential operational impacts.

To maximize safety of this alternative, flyover ramps and their approaches should be designed to minimize weaving between managed and general-purpose lanes. This would likely involve eliminating the need for vehicles to cross the managed lanes to make left turns at intersections with grade separation. When deciding at which intersections to deploy flyover ramps, increased safety benefits can also be gained by prioritizing intersections shown to have the highest frequency of crashes. Furthermore, installing full-width shoulders on at least one side of the flyover ramp is advisable to maximize safety and allow emergency access.

ITS Infrastructure

The alternatives proposed will require different technology solutions to implement with varying levels of cost and complexity. Necessary upgrades may include installation of toll points, variable toll message signs, dynamic electronic signage, extension of the existing fiber optic backbone, and additional closed circuit television cameras and vehicle detection devices. The use of each of these technologies will be dependent on the alternative; however Alternative 4 and Alternative 5 will likely require the greatest investment in ITS infrastructure as these will make use of variable tolling. However, revenue from tolling could be used to supplement ITS implementation and improvements along the corridor. Alternative 1 and Alternative 3, which will keep HOV lanes un-tolled, could make use of ITS infrastructure for enforcement (further discussed in another section) or dynamic message signs that show travel times in general and high occupancy lanes.

Determining which technologies to use is a vital step in converting HOV lanes to HOT lanes to ensure adherence to US codes [11].

TOLL COLLECTION

Automatic Vehicle Identification (AVI) technology for collecting tolls is common and widely used across the United States. The most common technique makes use of radio frequency identification (RFID) which employs an antenna that communicates with a transponder located in a vehicle [27]. Tolls can be collected at strategic locations (mainly ingress points), with AVI antennas placed on overhead structures above the tolled lanes. Cantilever structures can be used where space is minimal and tolling locations span a short distance (Alternative 4), or can be placed on structures that span entire sections of a roadway. Colorado already makes use of the ExpressToll system. Other examples include E-ZPass (Eastern United States), SunPass (Florida), and PeachPass (Georgia) [27]. Tolls can be charged to a customer account or debited against an account balance that drivers regularly replenish when needed. Alternative 4 and Alternative 5 would require the implementation of tolling technologies. The basis for the improvements that these alternatives offer is the option for single occupant vehicles to access the HOV facility through the payment of a toll. In Alternative 4, toll points would need to be strategically placed away from left turning traffic at intersections to ensure crossing vehicles aren't charged. Alternative 5 would likely have more options for toll point placement as the lanes would be separated more often from non-tolled traffic.

DYNAMIC TOLLING AND SIGNS

While CDOT currently only uses time-of-day pricing on tolled lanes, the agency is working to implement the capability to dynamically adjust tolls to account for congestion and other factors. The potential to manage demand for HOT lanes in this way is a major benefit of constructing these facilities. Authorities can respond to congestion issues by raising or lowering toll prices on HOT lanes to artificially create or reduce demand. Variable/dynamic message signs can be strategically placed along a corridor to convey changing prices, travel times, and incidents to drivers. Messages can be easily changed from Traffic Operation Centers where travel conditions can be monitored. These signs can come in several configurations including the ability to show any message that needs to be conveyed in real time (travel times, construction, tolls, crashes, weather conditions). Signs can also show static information (such as route numbers) and include dynamically changing information such as tolling and travel times [27]. Similar to toll collection, signs displaying toll prices would need to be strategically placed to allow motorists enough time to make the decision of whether they would want to use the toll lanes. Alternative 4 and Alternative 5 would each need careful consideration on the location of these signs due to the multiple access points along Santa Fe Drive. All alternatives, with the exception of Alternative 2, could make use of dynamic signs to convey traffic conditions along the corridor. Displaying travel time savings may encourage drivers to carpool if they realize the potential differences in travel along the HOV lane when compared to the general-purpose lanes.

CORRIDOR MONITORING

To evaluate the status and ongoing reliability of managed lane facilities, it is important that system operators have technologies in place to monitor conditions. In order to carry out this obligation, specific technologies can be employed to monitor traffic conditions. Closed-Circuit Television (CCTV) can be placed at strategic locations along corridors to visually monitor traffic conditions, while other devices such as Microwave Vehicle Radar Detectors (MVRD) and connected vehicle roadside units (RSUs) can be used to evaluate travel time and speeds [28]. These technologies would allow authorities to dynamically change toll prices to increase or reduce demand for the express lane.

COMMUNICATIONS UPGRADES

Most alternatives presented in this paper would benefit from extension of the existing fiber optic backbone on Santa Fe Drive to cover the entire length of the study corridor. Currently, CDOT only has fiber optic infrastructure on Santa Fe south of Dartmouth Ave. Extending this backbone would allow variable/dynamic message signs, CCTV cameras, and tolling stations reliable communications to update and collect information in real time to manage the corridor. All of CDOT's tolled lanes currently communicate via fiber optic infrastructure. Alternative 4 and Alternative 5 would likely require full fiber optic implementation along the entire corridor for tolling and dynamic signage. Alternative 1 and Alternative 2 could make use of fiber optic upgrades if enforcement technology or dynamic message signs were to be implemented.

Violations and Enforcement

Violations can occur when riders determine that the risk of being caught and consequences of using managed lanes when they are not authorized to do so do not outweigh the potential for time savings from using managed lanes. Violation rates will likely vary widely depending on the facility design (barrier type, ingress/egress points), toll costs, and driver attitudes towards the project. Based on a survey report in 2003, rates can vary from around 1% to as high as 40% on policed roadways [29]. Violations can cause negative publicity for an HOV project. The public may perceive violations as an indication of HOV lane failure. Violations may also cause issues with congestion on express lanes if sufficient violations occur. There are several enforcement techniques employed in HOV and HOT lanes to combat these problems.

POLICE ENFORCEMENT

Police presence is often used to enforce occupancy requirements through visual observations. However, facilities for policing and methods can vary widely by state [29]. In examples like SR-167 in Seattle or the Katy Freeway in Texas, officers are situated on the shoulder of toll plazas and watch for violators [10] [30]. On I-25 in Colorado, enforcement zones are built into medians and separated from traffic using barriers. To capture violators, police will make use of both decals sold to eligible drivers (ex: I-95 in

Florida) or transponder beacons at specific locations that indicate to officers of valid and invalid users [30]. Officers will look for signs of violation based on these parameters.

TOLL TRANSPONDERS

This method commonly occurs on HOT lanes where electronic tolling occurs via a transponder. The presence of a toll transponder on a vehicle can verify and detect vehicles that are properly registered with the transponder service. Additionally, it can also identify violators who are trying to access the express lanes without the proper transponders or settings and alert police enforcement as discussed above. Fees can be administered to violators via license plate detection technology.

IN VEHICLE DETECTION (CONNECTED VEHICLE TECHNOLOGY)

These include technologies that are equipped in a vehicle or carried by passengers. Examples are weight sensors for air bag deployment, seat belt sensors, and personal cellular devices [30] [31]. The technology for this detection is still emerging [31].

ROADSIDE DETECTION

Violation technologies can be deployed at key points on an HOV/HOT lane to automatically capture and evaluate vehicles that are violating occupancy requirements. These setups often include multiple camera angles which capture front and side windshield for vehicle occupancy purposes, and a rear camera for license plate identification in the case of a violation [29]. Alternative technologies can include infrared detection and microwave detection [30]. Despite past issues with the use and implementation of these technologies, the use of video detection is being implemented and new research is being conducted to capture riders violating carpool requirements [30] [32] [31]. In addition, violators can be identified at toll stations or other locations using license plate detection.

It should be noted that enforcement techniques and their impacts on violation rates vary widely. Different agencies make use of different policing departments depending on project contracts and available resources [29]. In addition, the available facilities (ex: shoulders) for police activity will vary by project, state, and area. Evaluation of enforcement effectiveness on I-15 in San Diego suggested that more citations do not correlate with a change in violation frequency [33]. In a study on the effects of saturation enforcement on I-66 and I-395 in Virginia, it was concluded that increased enforcement did not reduce violations in subsequent days [30]. In the case of NJ 1-80 and I-287, violations were highest during fixed three-day schedule monitoring, which motorists exploited by using HOV lanes in afternoons when they did not see police activity in the AM [34].

In the context of Santa Fe Drive, violations would likely be greatly reduced if the managed lane facilities offered adjacent spaces for officers to safely park and look for violators. Alternative 5 could provide the greatest freedom in planning an enforcement strategy as a redesign of the corridor could include extra shoulder or median space for enforcement activities. In addition, Alternative 4 and Alternative 5 would allow for the implementation of some of the techniques listed above through integration with added ITS technologies. Alternative 1 and Alternative 3 could make use of roadside detection and could be a cost effective way at minimizing violations. Right-side HOV lanes would also provide police officers with traditional sentry locations to watch for violators.

HOV Lanes on Signalized Arterials

HOV lanes on arterials are used to improve travel time and reliability, although they are uncommon compared to HOV and HOT lanes on freeways. One of the most commonly used forms of HOV lanes on arterials in urban areas is bus rapid transit (BRT) lanes which are designated for transit use only. In some cases, carpool vehicles are also allowed access to these facilities [35]. Arterial HOV lanes are constructed using a wide variety of design and operational features. Access type varies based on facility, but typically includes limited or continuous access. The use of physical separation appears to be uncommon or nonexistent on arterial HOV facilities, which is logical considering the need for frequent entry and exiting from general traffic to access left and right turns at intersections. Studies to evaluate effectiveness of these specific facilities appear to be limited, but strategies for implementation and improvements do exist.

Various configurations of HOV lanes and strategies employed include left-side lanes, curb lane, second lane, and center lane facilities [36]. Evaluation of existing facilities reveals that most HOV lanes on arterials are located in the far left lane (Kalaniana'ole Highway [HW], Santa Fe Drive [CO]), are open to carpools and located on the right side of the roadway (Capitol/Central/Lawrence/San Toma Expressway [CA], Smith/Fannin/Travis/Milam Street [TX], N Washington Street [VA], State Highway South [WA], Airport Road [WA]), or are right lanes dedicated to bus facilities [37]. Land usage and limiting access points to the roadway can reduce frequent lane changes and conflicts for curb-lane HOV facilities. **Table 5** covers some of the design and operational features of HOV lanes that are located on signalized arterial roadways.

Table 5. Examples of Arterial HOV Lane Features [37]

Facility	***Buffer***	***Striped Shoulder***	***Access***	***Side of Road***	***Occupancy***	***Hours***
Santa Fe Drive	Solid White Line	~4-6ft	Continuous	Left	2+	6-8:30AM (NB) 4-6:30PM (SB)
Capitol/ San Tomas/ Central/ Lawrence Expressway– California	White Dashed Line	3-7ft	Continuous	Right	2+/Bus	6-9AM 3-7PM
Klaniana'Ole Highway- Hawaii	Double Yellow Dashed Line	~1ft	None	Left WB (AM) Left EB (PM)	2+	5:30-8AM (Contraflow) 3:30-6PM (Concurrent)
Smith/ Fannin/ Travis/ Milam Street- Texas	White Solid Line	N/A	Continuous	Right	3+/Bus	7-9AM 4-6PM
North Washington Street- Virginia	White Dashed Line	N/A	Continuous	Right	2+/Bus	7-9AM (SB) 4-6PM (NB)
State Highway South (SR99)- Washington	White/Solid Dashed Line	N/A	Continuous/ Limited (near intersections)	Right	2+/Bus	24/7
Airport Road- Washington	White/Solid Dashed Line	~5ft	N/A	Right	2+/Bus	5:30-8:30AM (NB) 2:30-5:30PM (SB)

Despite these strategies and existing facilities, arterials have drawbacks with respect to HOV lanes. Signalized intersections can provide progression issues for travelers expecting smooth rides through HOV lanes, and numerous access points to the arterial provide a lot of friction for motorists entering or crossing over HOV lanes. Conflicts with left and right turn movements from general-purpose lanes can cause safety and delay issues [35]. In a 2015 Florida Department of Transportation survey, only 9 of 25 participants said that some form of HOV lane could improve traffic conditions on arterials in their respective districts (5 said no and 11 said maybe) [38]. The responses were less sure for HOT and express toll lanes. As it pertains to Santa Fe Drive, the HOV lanes had originally been open to buses in addition to carpools. However, with the introduction of a parallel light rail line, the HOV lanes are primarily used by drivers choosing to carpool.

HOV to General-purpose Use Conversion

Conversion of HOV lanes to general-purpose lanes appear to be relatively rare. There are significant legal barriers that come into play when considering this strategy, particularly if federal funds were used. Most projects typically convert HOV lanes to HOT lanes to address operational issues. One example of a HOV to general traffic lane conversion project would I-80 and I-287 in New Jersey [34]. Occupancy included vehicles with 2+ riders, buses, and vanpools and the lanes were only separated by painted lines with access the entire length. Initial public support for the I-80 HOV lanes deteriorated with high violation rates and congestion issues from the I-287 HOV lane [34]. A combination of delays from construction, violations, and low utilization caused negative publicity for I-287, and subsequently I-80. Funding for I-287 came from the Transportation Appropriation Bill. In order to convert the HOV lane back to a general-purpose lane in 1998, the state required congressional action to approve of the redesignation and avoid repaying the funds [34]. While waiting for congressional approval on the federal level, the state passed legislation to change hours of occupancy requirements to off-peak hours, allowing single occupancy vehicles to access the lanes during peak periods [34]. A study proving the inadequacy of the HOV lanes in reducing congestion and improving air quality was required and presented and the lane was closed in 1998 [34]. HOV lanes on both roads were converted to general-purpose lanes less than a year after I-287 HOV was opened to the public. It was found that mode shifts on both roads had been minimal, and high occupancy was not converted from users of the freeway but came from other facilities [34].

Alternative 2 calls for the conversion of the HOV lane on Santa Fe Drive to a general-purpose lane. Despite possible legal barriers, this option remains relevant due to the cost implications of grade separation of the managed lane alternatives and potential operational improvements. The concept of converting HOV lanes to general-purpose lanes on Santa Fe Drive has been discussed in the past. In 2013, an assessment of the corridor found that converting the HOV lanes to general-purpose lanes could significantly improve peak AM and PM performance, air quality benefits, and travel time [1]. The report further concluded that managed lane options would require traffic and revenue studies. The legal implications of this alternative are further discussed in a separate section.

HOV to HOT Conversion
No research was able to be found related to converting HOV lanes to HOT lanes on arterial roadways. However, there are numerous examples of these types of lane conversions on freeways.

Florida's Department of Transportation (FDOT) recognized issues with growing congestion on general-purpose lanes and violations of HOV lanes that had been constructed on I-95. The decided solution was to convert the HOV facility to HOT lanes in 2008 [39]. Single HOV lanes in each direction were converted into two HOT lanes in each direction by reducing general-purpose lane width (from 12ft to 11ft) and reducing the buffer width to 1ft [39]. There was a total of three tolling segments where pricing could be dynamically adjusted based on congestion and demand. Occupancy requirements for toll exemption increased from 2+ per vehicle to 3+ per vehicle [39]. These upgrades were largely beneficial; express lane travel times decreased in portions of I95, while speeds in the express lanes were about 15mph higher than general-purpose lanes [40]. The success of this conversion led FDOT and multiple other agencies in Florida to expand the express lane program from the initial 7 miles to a total of 21 miles between Miami and Fort Lauderdale [40] [41].

The MnPASS project on Minnesota's I-394 and I-35W converted underutilized HOV lanes into managed HOT lanes due to mounting political and public pressure [39]. The new HOT lanes made use of electronic tagging and were opened in 2005 on I-394 and in 2009 on I-35W. I-394 was designed using both painted separation (single lane in each direction) and reversible-barrier separated (two lanes) HOT lanes with restricted ingress points. This design feature was selected largely in part due to a small number of interchanges making up the bulk of the demand for I-394 [42]. I-35W was designed using painted line separation and frequent ingress points due to the frequent access ramps [42]. Both designs allow vehicles with occupancy of 2+, transit, and motorcycles to use the lanes for free during peak hours, while single occupancy vehicles can use the lanes for a fee that dynamically changes based on demand [43]. The MnPASS project resulted in an increase to person throughput and still maintained the required 45 mph in the managed lane during peak hours for more than 90% of the time [43].

In Washington State, increasing economic opportunities and population growth led to an interest in conversion of existing HOV lanes on I-405 to HOT lanes to mitigate predicted congestion and maintain transit reliability along the corridor [39]. Single and dual express lanes using dynamic tolling were constructed in 2015 in the northern portion of the project area; further express toll lanes are planned to be constructed in 2024 to connect with existing HOT lanes on SR-167 [44]. Free ridership is available to those with an occupancy of 3+ during peak hours and is also available to transit and motorcycles. Separation and access are setup using dual white stripes with access points designated by dashed pavement markings. Results varied based on location and number of express lanes [45]. According to a report in 2017, dual-lane sections maintain the target operating speed of 45mph 90% of the time and saw average speed increase for both express lanes and general-purpose lanes. Single lane sections, however, only maintain the target operating speed of 45 mph for 72% of the time and saw decreases in average travel speed in the southbound directions. Travel times were lower across the board for express lanes when compared to general-purpose lanes, however travel times in single express lane sections were higher during peak period travel [45].

Houston and its surrounding radial freeways have gone through several iterations, conversions, and additions of HOT lanes. Rapid population growth and growing congestion led agencies to consider solutions for increasing quality of service. HOV lanes were constructed on the Katy Freeway (I-10) in 1984 following the successes of HOV lanes on I-45 [39]. The original HOV lane was separated from general traffic using a barrier and was reversible. Buses and vanpools were the only vehicles allowed on the HOV lanes on I-10. Low utilization rates led METRO to allow vehicles with 4+ occupancy to access the HOV lane, and varied between 4+ and 2+ through 1995 [10]. In 1995, 2+ occupancy vehicles could access the lane for $2 per trip. However, in 1995, TxDOT determined that the Katy Freeway would require reconstruction. Construction was completed in 2009 and included a 4 lane HOT system with 2 lanes in each direction. The new HOT lanes were separated from general traffic using pylons and a buffer [10]. In the few years after construction, managed lanes were showing greater speeds and lower travel times when compared to the general-purpose lanes [10].

Conversion of HOV lanes to managed toll lanes has been largely beneficial for many freeways facing issues of under-utilization and general-purpose lane congestion. The ability to offer drivers the option to pay for HOV lane access produces revenue that can be used for transit projects or to help fund conversion costs. It also reduces congestion on the general-purpose lanes by removing drivers willing to pay the toll. These examples hold valuable insight into ways that Alternative 4 and Alternative 5 can be successful. These alternatives would require several techniques and strategies that were implemented in these examples and drawing from this past experience could be invaluable.

Laws, Legislation, and Requirements

While decisions to modify a HOV lane made from a strictly operational and design standpoint may be appealing, there are several legal considerations that must be considered. As mentioned earlier, the original construction of the HOV facility in the 1980's was built with a lane to accommodate bus transit and encourage carpooling [1]. Interestingly, this facility was constructed while HOV standards were new and still evolving [46]. Today, Santa Fe Drive does not meet several current HOV lane requirements [46]. Research into the origins of this facility produce mixed results on the use of funding from the Congestion Mitigation and Air Quality Improvement Program (CMAQ); however the most recent references state these funds were utilized to some degree [1] [46] [47]. For context, CMAQ is a program established in the early 1990s that provides federal funding to transportation projects that contribute to improvements in air quality [48]. It was part of the larger Clean Air Act movement and has been reauthorized in every transportation bill since its conception [48]. The implications of the use of CMAQ funding include specific actions and requirements when building HOV lanes or upgrading to HOT lanes. These requirements are found in US Title 23 Chapter 149.

> *Title 23 U.S. Code § 149 - Congestion mitigation and air quality improvement program* [49]
> This code sets requirements for the use of funding through the CMAQ program. This code says that States may use funds set aside for it under CMAQ in areas designated as nonattainment zones or that were designated as nonattainment zones in the past. Santa Fe Drive, being fully located in both Denver and Arapahoe Counties, falls within the non-attainment zone (does not meet national air quality standards) for ozone as of 2021 [50]. Additional requirements for the use of these funds are included in section 149(b)(1-9), one of which being the construction of high occupancy vehicle lanes and improving traffic flow that 'mitigate congestion and improve air quality' [section 149(b)(5)].

As it pertains to the alternatives in this paper, conversion of the HOV lanes in a way that offers capacity to single occupancy vehicles may be restricted under this code since CMAQ funds were used for this facility [47] [51]. Section 149(c)(3) specifically reads:

> "No funds may be provided under this section for a project which will result in the construction of new capacity available to single occupant vehicles unless

> the project consists of a high occupancy vehicle facility available to single occupant vehicles only at other than peak travel times."

Whether this refers to adjustments made to a project decades after initial construction is not specified. However, it would be reasonable to assume that the use of CMAQ funds to construct lanes and subsequently provide capacity to single occupancy vehicles would in essence be using these funds in a way that contradicts the CMAQ program goals of congestion management and improving air quality. Re-designation of the HOV lane to a general-purpose lane under Alternative 2 may require FHWA approval and refunding of funds that were used under CMAQ for the design, construction, and ROW of the facility [34] [47]. In addition, Colorado Title 42-4-1012(b)(V) prohibits the conversion of a HOV lane to a HOT lane if the conversion will result in the loss or refund of federal funds [52]. Therefore, if CMAQ funding was used and would need to be refunded, then it would take an act of Colorado legislation to convert the HOV lane to HOT lanes unless specific requirements are met. Colorado Title 42-4-1012(b)(V) does not specifically prohibit conversion of an HOV lane to a general-purpose lane if funds need to be repaid.

As it pertains to Alternative 4 and Alternative 5 Title 23 Chapter 166 provides stipulations on access of single occupant vehicles to HOV lanes.

Title 23 U.S. Code § 166 – HOV Facilities [11]

> Code § 166 states the occupancy for HOV facilities should not be fewer than two occupants. However, Section 166(b)(4)(A-C) specifically address the instances for which a HOV lane can allow non-exempt vehicles access to the facility. In order to do this for single occupant vehicles, the public authority needs to establish a program for motorists to enroll and pay for tolls, have a system for collecting tolls, prove the facility is not currently degraded, and establish procedures for managing demand through dynamic tolling, enforcement, monitoring, and provide "over-the-road-buses" the same access as public transportation buses. Section 166(d) provides specific requirements (discussed later) to be met if non-exempt vehicles are allowed access to the lanes. Facility compliance by maintaining specific speeds is a vital requirement per this section, and must be addressed if the facility falls below the standards.

This code, if it overrides or takes precedence over Title 23 U.S. Code § 149, would allow for the conversion of the HOV lane to HOT lanes even if CMAQ funds had been used to initially build the Santa Fe Drive HOV lane. This could avoid repayment of CMAQ funds which would satisfy Colorado Title 42-4-1012(b)(V). Additionally, if funds under CMAQ are still being apportioned to Colorado, then managed lane alternatives may be eligible to use Federal-Aid Highway funds set aside for the state of Colorado under Title 23 U.S. Code § 149, as the project area falls within a nonattainment zone (Section 149[b]) and is discussed in the regional MPO. Using funds under these alternatives would also require that the project improves traffic flow, improve transportation systems management and operations, or increase vehicle occupancy rates among other options [49].

HOT Requirements

Title 23 U.S. Code §166 (d)(1-2) lays out the requirements to allow tolling of single occupant vehicles that access HOV lanes [11]. The first step in doing so is by conducting a study and creating a report proving that the facility is not already degraded and that opening the facility to single occupant vehicles will not cause the corridor to become degraded. In this context, a degraded facility is one in which vehicle speeds drop below the minimum average operating speed 90% of the time during morning and evening weekdays over a consecutive 180-day period. Minimum operating speed in the case of Santa Fe Drive would be 45mph as the speed limit is over 50mph (55mph is the speed limit on Santa Fe Drive). In addition, the local authority would be subject to the following when converting the facility to include this type of tolling:

1. Establish, manage, and support a performance monitoring, evaluation, and reporting program to determine the impact that the tolled vehicles have on the operation of the facility and adjacent highways.
2. Establish, manage, and support an enforcement program.
3. Limiting and discontinuing the use of the facility by single occupant vehicles when the facility becomes degraded.
4. Bring the facility within degradation definition compliance by:
    a. Increasing occupancy requirements
    b. Varying the toll
    c. Discontinuing non-HOV vehicles access to the facility
    d. Increasing available capacity of the HOV facility
5. Loss of federal funding for this and other projects if compliance to degradation rules is not maintained.
6. Potential waivers for failure to meet compliance can be passed if it is in the best interest of the public, compliance is reestablished, or a good faith effort was made to improve the facility.

Alternative 4 and Alternative 5 are the only alternatives subject to these rulings. Existing conditions analysis based on past studies show general traffic speeds to be at or below the 45mph threshold throughout the facility [1] [47]. Further investigation would be required to ensure current HOV facility operations would not be degraded and would not become degraded with either alternative. These additional steps add an additional dimension to these two alternatives' legal barriers.

While this section attempted to condense some of the laws and legislation surrounding the alternatives suggested in this paper, further legal and legislative investigation should be explored. In addition, confirmation of when and how much CMAQ funding was used on Santa Fe Drive HOV lanes would be necessary. Below is a list of suggestions for progressing the alternatives on Santa Fe Drive as far as CMAQ funding is concerned. In addition, an example of the steps that may be required for various alternative implementation are presented in **Figure 3**.

1. Determine how much CMAQ funding was used on the HOV lanes of Santa Fe Drive.
2. Determine if other federal funding aid was used on the HOV lanes of Santa Fe Drive.
3. Determine if any alternatives can currently access CMAQ and other Federal Aid funding.
4. Coordinate with FHWA to determine if and how CMAQ funding must be returned.

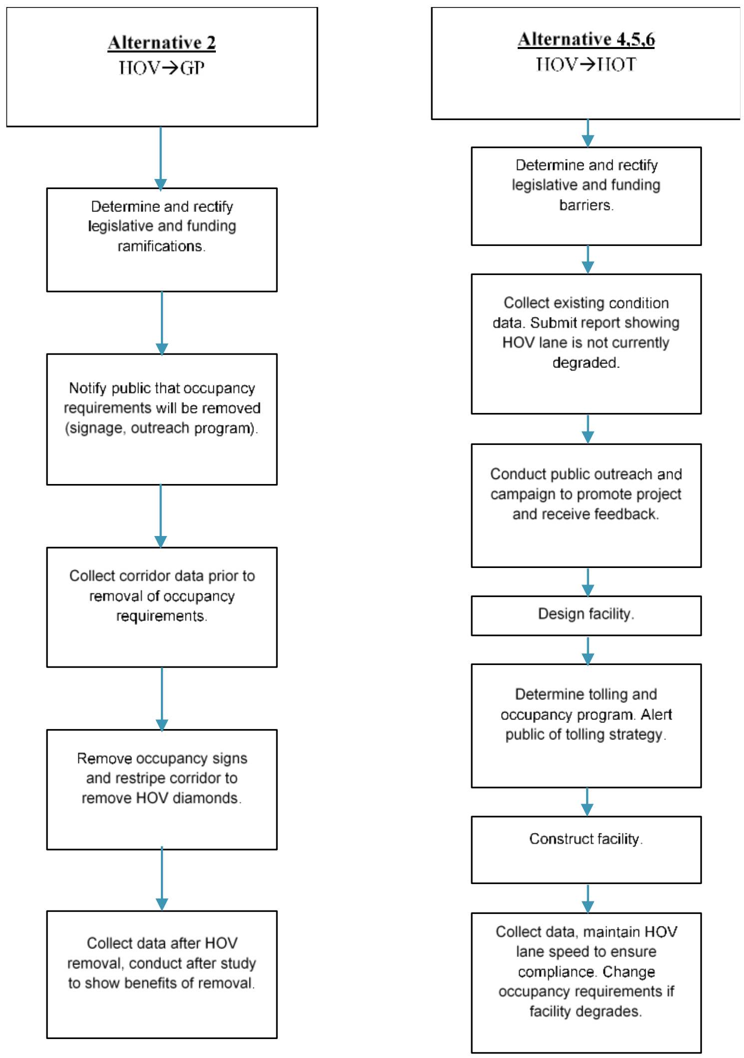

Figure 3. Important Steps to Implement Alternatives and Adhere to Legislative Requirements

Alternative Operational Analysis

Taking into consideration the wide variety of experiences, improvements, and projects that have been carried out nationally on HOV and HOT lanes offers a solid foundation in determining which alternatives may be best suited for Santa Fe Drive. However, there are also analysis tools available to further aid in these decisions. To further enhance this research, available data was evaluated using the high-level POET-ML tool which considers conditions on HOV facilities and how various policy shifts might impact performance.

Specific segments that were analyzed using POET-ML can be seen in **Appendix I**. **Table 6** outlines the projected 2040 traffic volumes associated with each. Except for Alternative 1 and Alternative 3, each alternative will include eight total lanes on Santa Fe Drive between Alameda Avenue and Evans Avenue, and six total lanes between Evans Avenue and C-470. This will require an additional through lane to be constructed starting near Bowles Avenue and extending to C-470.

Table 6 - Level 2A Corridor Analysis Alternatives

Alternative	Roadway Classification	Description of Alternative	Projected 2040 Traffic Volumes (veh/day)				
			Seg 1	***Seg 2***	***Seg 3***	***Seg 4***	***Seg 5***
Alt 1, Alt 3	Expressway	Minor changes to HOV lane	106,190	97,850	78,040	63,790	60,200
Alt 2	Expressway	Conversion of existing HOV lane to GP lane	108,920	100,000	84,840	79,160	75,310
Alt 4	Expressway	Enhanced at-grade managed lane from C-470 to I-25	108,540	99,300	84,590	78,020	74,170
Alt 5	Expressway	Enhanced managed lane from C-470 to I-25 including grade separation at major intersections	108,540	99,300	84,590	78,020	74,170

To evaluate and compare each of the alternatives, the POET-ML tool was used to evaluate the southbound PM Peak Hour operations. A description of the assumptions applied are outlined on the next page followed by a summary of the values used within the analysis in **Table 7**.

Assumptions Used in POET-ML Analysis

The following segment boundaries were used for this analysis. The spot location where projected traffic volumes were calculated for each segment is listed in parentheses.

- Segment 1 – I-25 to Evans Avenue (North of Florida)
- Segment 2 – Evans Avenue to Dartmouth Avenue (North of Dartmouth)
- Segment 3 – Dartmouth Avenue to Belleview Avenue (North of Belleview)
- Segment 4 – Belleview Avenue to Mineral Avenue (South of Church)
- Segment 5 – Mineral Avenue to C-470 (South of Mineral)

Evans Avenue was used as the boundary between Segments 1 and 2 because it is the location where the alternatives change between four lanes to the north and three lanes to the south. Belleview Avenue was used as the boundary between Segments 3 and 4 because it is roughly where the existing HOV lane ends.

Southbound ADT values used for this analysis because peak hour volumes are greater than northbound peak hour volumes.

Free flow speed (FFS) for all alternatives were assumed to be 5 MPH above the lowest current posted speed on the segment.

Lane capacity for all alternatives was calculated based on the formula below from the FHWA document “Simplified Highway Capacity Calculation Method for the Highway Performance Monitoring System” [53].

$$Capacity = \frac{g}{C} x \; Lanes \; x \; 1{,}900$$

**Where g/C = Overall green time*

Overall green time for GP lanes and ML lanes without grade separation was assumed to be 60%. Overall green time for ML lanes with grade separation was assumed to be 100%.

Daily lane capacity was calculated based on an hourly-to-daily effective capacity factor of 12.

Table 7. Values Used for POET-ML Analysis

Alternative	Segment	Seg Length	SB AADT	Peak Hour %	SB Peak Hr Vol	GP Lanes	ML Lanes	FFS	GP Vol Total	ML Vol Total	GP Lane Capacity	ML Lane Capacity	Daily GP Lane Capacity	Daily ML Lane Capacity	GP LOS	ML LOS
Alt 1, 3	1	2.0	52750	10.3%	5434	4	0	50	5434	0	1140	N/A	13680	N/A	F	N/A
	2	1.8	49680	10.3%	5118	2	1	60	4248	871	1140	1140	13680	13680	F	C
	3	2.1	39470	9.7%	3829	2	1	60	3178	652	1140	1140	13680	13680	F	C
	4	3.2	32670	9.6%	3137	2	0	50	3137	0	1140	N/A	13680	N/A	F	N/A
	5	1.1	31790	9.0%	2862	2	0	55	2862	0	1140	N/A	13680	N/A	F	N/A
Alt 2	1	2.0	55070	10.3%	5673	4	0	50	5673	0	1140	N/A	13680	N/A	F	N/A
	2	1.8	51010	10.3%	5255	4	0	60	5255	0	1140	N/A	13680	N/A	F	N/A
	3	2.1	43170	9.7%	4188	3	0	60	4188	0	1140	N/A	13680	N/A	F	N/A
	4	3.2	42370	9.6%	4068	3	0	50	4068	0	1140	N/A	13680	N/A	F	N/A
	5	1.1	41230	9.0%	3711	3	0	55	3711	0	1140	N/A	13680	N/A	F	N/A
Alt 4	1	2.0	55000	10.3%	5665	3	1	50	4810	855	1140	1140	13680	13680	F	C
	2	1.8	50650	10.3%	5217	2	1	60	4362	855	1140	1140	13680	13680	F	C
	3	2.1	42980	9.7%	4170	2	1	60	3315	855	1140	1140	13680	13680	F	C
	4	3.2	41560	9.6%	3990	2	1	50	3135	855	1140	1140	13680	13680	F	C
	5	1.1	40420	9.0%	3638	2	1	55	2783	855	1140	1140	13680	13680	F	C
Alt 5	1	2.0	55000	10.3%	5665	3	1	50	4240	1425	1140	1900	13680	22800	F	C
	2	1.8	50650	10.3%	5217	2	1	60	3792	1425	1140	1900	13680	22800	F	C
	3	2.1	42980	9.7%	4170	2	1	60	2745	1425	1140	1900	13680	22800	F	C
	4	3.2	41560	9.6%	3990	2	1	50	2565	1425	1140	1900	13680	22800	F	C
	5	1.1	40420	9.0%	3638	2	1	55	2213	1425	1140	1900	13680	22800	E	C

Entering this data in the POET-ML tool generated a future V/C ratio value for both the managed and general-purpose lanes for each corridor segment within each alternative. The results of this analysis are outlined in **Table 8**.

Table 8 – 2040 Southbound PM Peak Hour Volume and V/C Ratio

	Lane Type	Segment 1		Segment 2		Segment 3		Segment 4		Segment 5	
		V/C	*VPH*	*V/C*	*VPH*	*V/C*	*VPH*	*V/C*	*VPH*	*V/C*	*VPH*
Alt 1,3	***GP***	1.19	5434	1.86	4248	1.39	3178	1.38	3137	1.26	2862
	ML	N/A	N/A	0.76	871	0.57	652	N/A	N/A	N/A	N/A
Alt 2	***GP***	1.24	5673	1.54	5255	1.22	4188	1.19	4068	1.09	3711
	ML	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Alt 4	***GP***	1.41	4810	1.91	4362	1.45	3315	1.38	3135	1.22	2783
	ML	0.75	855	0.75	855	0.75	855	0.75	855	0.75	855
Alt 5	***GP***	1.24	4240	1.66	3792	1.20	2745	1.13	2565	0.97	2213
	ML	0.75	1425	0.75	1425	0.75	1425	0.75	1425	0.75	1425

An implicit assumption in this evaluation is that in alternatives that employ managed lanes, the toll rates will be adjusted to ensure an appropriate number of vehicles enter the lanes without degrading performance below acceptable operational levels for paying vehicles. The results show that for each alternative the general-purpose lanes are likely to operate at capacity during peak hours. This is not surprising, given the high vehicular demand from areas surrounding the corridor and lack of competitive alternate routes, which makes Santa Fe the most convenient route for a significant portion of the southwest Denver metropolitan area. The implication is that even as additional roadway capacity is added through corridor enhancements, there is significant unmet demand ready to backfill the corridor.

To further distinguish performance of the various alternatives, V/C ratio analysis was augmented with the 2040 southbound daily total vehicle hours of delay performance metric, as generated by POET-ML. This metric describes the amount of delay experienced by slow and stopped vehicles on a segment. The analysis shows that despite failing operating conditions during peak hours, over the course of an entire day, increased throughput capacity along the corridor can result in reduced daily vehicular delay. The assessment is high-level and based on preliminary information, but the assumptions applied for each alternative are the same; thereby allowing a relative comparison to be performed between alternatives.

Table 9- 2040 Southbound Daily Total Vehicle Hours of Delay

	Seg 1 *(2.0 mi)* Delay (GP)	Seg 1 *(2.0 mi)* Delay (ML)	Seg 2 *(1.3 mi)* Delay (GP)	Seg 2 *(1.3 mi)* Delay (ML)	Seg 3 *(2.7 mi)* Delay (GP)	Seg 3 *(2.7 mi)* Delay (ML)	Seg 4 *(3.2 mi)* Delay (GP)	Seg 4 *(3.2 mi)* Delay (ML)	Seg 5 *(1.1 mi)* Delay (GP)	Seg 5 *(1.1 mi)* Delay (ML)	TOTALS GP	TOTALS ML
Alt 1,3	3,978	N/A	8,904	125	3,254	46	5,647	N/A	1,225	N/A	23,008	171
Alt 2	4,720	N/A	6,180	N/A	2,906	N/A	4,735	N/A	1,024	N/A	19,565	N/A
Alt 4	5,782	156	9,893	116	3,852	137	5,630	250	1,091	74	26,248	733
Alt 5	3,494	259	5,650	194	1,812	228	2,524	416	438	131	13,918	1,228

The POET-ML results summarized in **Table 9** show the general-purpose and managed lane vehicle hours of delay by segment and totaled for each alternative. The results reveal managed lane delay totals increase as capacity and vehicles accessing managed lanes increase. However, alternative performance diverges in the total delay experienced in the general-purpose lanes. Alternative 2 shows improvement in delay totals since general purpose capacity is increased. Alternative 4 results in increased general purpose delay and managed lane delay as a result of higher volumes being attracted to the corridor. The increased capacity of Alternative 5's managed lane due to grade separated intersections allows a larger volume to use the lane. The POET-ML results show an increase in total delay in the managed lane, but a significant decrease in total delay on the overall corridor; this is because the capacity of the managed lane increases when grade separation is added, allowing more vehicles to move from the general-purpose lanes to the non-signalized managed lane.

This POET-ML analysis is generally consistent with recent more detailed VISSIM analysis performed along the SH 119 corridor for CDOT/HPTE. This detailed analysis considered three different alternatives for HOT lanes including the addition of a new lane designated as HOT, the conversion of a general traffic lane to HOT lane where three thru lanes exist in each direction today, and the addition of a new lane designated as HOT with grade separated structure to allow for continuous flow at intersections. Based on the SH 119 VISSIM analysis, in order to see significant improvements in throughput along the corridor as well as operations, HOT lanes need to be grade separated at signalized intersections. However, there are significant costs and design challenges associated with grade separation of HOT lanes at signalized intersections, including determining how the HOT lane will interact with left turning vehicles that need to either cross over the HOT lane or utilize space above/below the grade separated structure at intersections.

Corridor Reliability

An operational characteristic of the Santa Fe Drive corridor is that on the majority of days, there is either adverse weather, an incident on the corridor, or an incident on an adjacent alternate route that has the potential to influence corridor capacity and/or demand. The Santa Fe PEL Corridor Conditions Report found that only 24% of days exhibited "standard" conditions during peak hours, in which traffic was not impacted by such an event. Because fluctuations in capacity and demand are so frequent, the reliability of the corridor in the face of adverse conditions is of critical importance.

The existing HOV lane on the corridor is underutilized [1] [26], meaning that within the No-Build scenario lane capacity is wasted during periods of high congestion. Alternative 5 may increase utilization by replacing the HOV lane with a managed toll lane, providing access to this lane to any driver willing to pay the toll. By adjusting toll rates during peak periods, the number of vehicles that use the managed lane can be controlled to ensure adequate usage without overwhelming lane capacity. If toll rates are dynamically adjusted based on congestion levels, managed lane volume can be more carefully controlled, thus ensuring the reliability of the lane while maintaining appropriate travel times [27]. Alternative 4 would likely only increase utilization if travel time savings are realized for those using the facility based on dynamic tolling, but the travel time savings are not expected to be as significant in Alternative 4 compared to Alternative 5.

While data for HOV to tolled lane conversions was not available for highways in Colorado, other Colorado-based managed lane deployments can be used to draw conclusions regarding their ability to improve corridor reliability. For example, the I-70 Mountain Express Lane (MEXL) west of Denver exhibited a significant reduction in travel time variability after the managed lane was opened, as suggested by **Figure 4**. It should be noted that some of this improvement can be attributed to the addition of a third travel lane during times of congestion, but the relative consistency of travel times after deployment suggests that the ability to actively manage traffic using the managed lane increases corridor reliability. This improvement is promising for Alternative 5, which would exhibit some elements of a tolled freeway and added lanes.

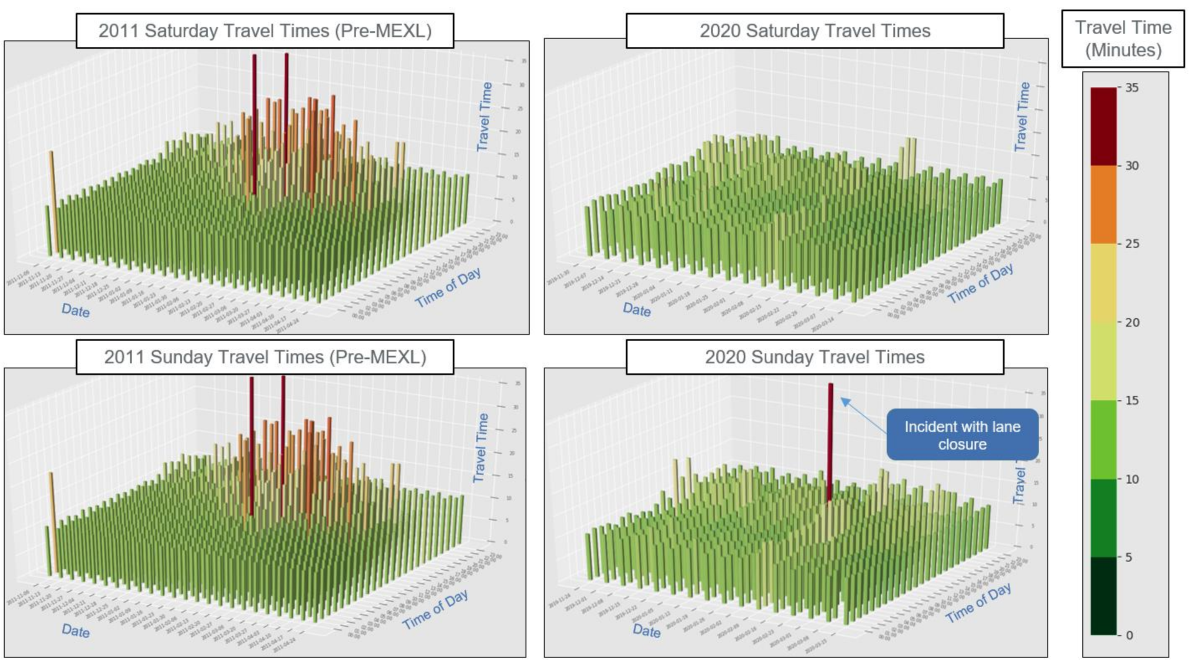

Figure 4. Average Travel Times Before and After Implementation of I-70 MEXL [54]

Safety Considerations

Each alternative presents unique safety benefits and challenges. Where there are many direct and indirect impacts to safety, the primary focus of this discussion is to evaluate the safety impact of each alternative as it relates to weaving conflicts, fixed object conflicts, speed differential conflicts, and intersection related conflicts. Qualitative safety conclusions for each alternative are provided based on a review of alternative characteristics as well as the frequency and severity of crash types associated with the improvements. All alternatives are compared to a No-Build scenario, which is assumed to match the existing condition of an HOV lane with no vertical separation.

Alternative 1 (Maintaining the HOV lane with design adjustments to improve operations and safety): ***Moderate Safety Improvement***

While improvements to the HOV lane have not been specifically defined, improvements could potentially include physical and operational modifications at intersections, wider or more defined separation between the HOV lane and general-purpose lanes, and increased shoulder width. These improvements are expected to result in a minor reduction in weaving conflicts. If vertical separation (delineator posts or concrete barrier) is added, fixed-object vehicle collisions would be expected to increase. If vertical separation is implemented continuously, a reduction in rear end collisions and sideswipe collisions between the lanes associated with speed differential is expected. Improvements at the intersections would be expected to reduce approach and broadside conflicts.

Alternative 2 (Conversion of existing HOV lane to a general-purpose lane): ***Moderate Safety Improvement***

In the existing condition, the alignment of left turn lanes at signalized intersections requires drivers making a left turn to merge into the HOV lane, presenting weaving conflicts. By converting the existing HOV lane to a general-purpose lane, drivers are provided with more distance to get into the correct lane prior to the intersection without fear of violation. This makes weaving movements less condensed, alleviating conflicts. This alternative assumes no vertical separation consistent with the No-Build scenario, therefore no additional fixed object crashes are expected. The conversion of the HOV lane to a general-purpose lane is expected to operate with speeds comparable to adjacent lanes, reducing sideswipe and rear end conflicts related to vehicles traveling at different speeds. Furthermore, an additional general-purpose lane is expected to reduce congestion and improve operations, potentially reducing rear end collisions in the existing general-purpose lanes. Approach and broadside intersection crash patterns are expected to be similar to the existing condition.

Alternative 3: (Relocation of the HOV lane from the left lane to the right lane to avoid left turn weave conflicts): ***Adverse Safety Impact***

Relocating the HOV lane from the left lane to the right lane will remove weaving conflicts associated with left turning traffic, while introducing weaving conflicts associated with right turning traffic at both signalized intersections, minor intersections, and driveways. Therefore, the safety impact as it relates to weaving and speed differential conflicts is expected to increase. Fixed object related conflicts are expected to remain comparable to existing conditions. In the existing condition, drivers are required to cross the HOV lane to make a left turn at some signalized intersections. In other cases, the HOV lane operates as a shared through/left turn lane. Removing HOV vehicles traveling through the intersection from the left most lane will reduce the potential for conflicts. However, HOV vehicles in the right lane are expected to experience great fluctuation in speeds and more conflict points along the corridor making the impact on intersection related crashes negligible in comparison to other alternatives.

Alternative 4 (Enhanced at-grade managed lanes from C-470 to I-25): ***Moderate Safety Improvement***

This alternative is assumed to include improvements similar to Alternative 1, with the conversion of the HOV lane to a HOT lane. This alternative is not expected to improve the weaving conflicts associated with drivers at intersections and may need to be considered near toll reader locations. Weaving may be potentially reduced along the corridor if managed lanes are installed with designated ingress and egress points, as opposed to a striped barrier with many conflict points as vehicles merge into and out of the HOT lane along the corridor. If the conversion to a HOT lane includes a vertical separation element, collisions with fixed objects is expected to increase. A HOT lane is expected to operate at speeds higher than the adjacent general-purpose lane, resulting in higher volumes of crashes related to speed differential between lanes. However, there is potential that a HOT lane may see higher utilization than the existing HOV lane, which could lead to a reduction in congestion and therefore rear end crashes in the general-purpose lanes. Approach and broadside intersection crashes patterns are expected to be similar to the existing condition.

Alternative 5 (Enhanced managed lanes from C-470 to I-25 including grade separation at major intersections): ***Significant Safety Improvement***

Grade separation is anticipated to be achieved by the installation of flyover ramps for HOV lanes to bypass major intersections. Similar safety impacts related to the conversion of the HOV lane to an HOT lane are expected as identified in the discussion of Alternative 4. Additionally, weaving conflicts due to vehicles merging into and out of the HOT lane are expected to be reduced as the grade separation reduces ingress and egress opportunities. Grade separation will include the construction of concrete barriers, resulting in an increase in fixed object crashes, particularly due to higher speeds as vehicles are not required to stop at some intersections. However, limited interaction is expected between the HOT lane and adjacent general-purpose lane, so higher speeds are not necessarily associated with speed differential related crashes such as sideswipe collisions between lanes. Approach and broadside crashes at intersections associated with the HOV/HOT lane are expected to significantly decrease.

Relevant Crash History

The existing crash history was evaluated to identify current crash patterns associated with weaving conflicts, fixed object conflicts, speed differential conflicts, and intersection related conflicts on Santa Fe Drive. The crash history was evaluated using crash data provided by CDOT for 2016-2018.

While it cannot be determined if crashes were specifically associated with the existing HOV lane, analyzing the crash history along the corridor can identify trends and hot spots where HOV improvements could be targeted to see the highest safety benefit. Additionally, evaluating the crash history can determine which crash types are most frequent, and which result in the highest injury severity. This allows the positive and negative safety benefits of each alternative to be compared relative to each other. **Figure 5** shows heat maps for each of the crash types evaluated.

Crashes that occurred as a result of weaving conflicts were identified as sideswipe crashes that occurred in the same direction. 445 sideswipe same direction crashes occurred on the corridor. The average speed of vehicle one (typically the vehicle identified ‘at fault’) was 27 miles per hour (mph). Of the 445 sideswipe crashes, 46 (10%) resulted in a fatality or injury. The average speed of the fatal and injury sideswipe crashes was 32 mph. Sideswipe same direction crashes were common along the corridor between Iowa Avenue and Mississippi Avenue.

To evaluate the crashes that occurred as a result of a fixed object that would be associated with vertical separation, fixed object crashes that involve barricades, bridge rail, concrete barrier, delineator posts, and guard rail were considered. 53 of these crashes occurred on the corridor, with the average speed of vehicle one of 43 mph. Of the 53 fixed object crashes, 14 (26%) resulted in an injury. The average speed of the injury fixed object crashes was 42 mph. Fixed object crashes were common along the corridor between Belleview Avenue and Union Avenue.

Non intersection rear end crashes where both vehicles were traveling over 20 mph were identified to evaluate crashes along the corridor associated with speed differential. 116 of these crashes occurred, with the average speed of vehicle one of 41 mph. 25 (21.5%) of these crashes resulted in an injury. The average speed of the injury crashes was 44 mph. These speed differential crashes were common near Dartmouth Avenue and Oxford Avenue.

Approach and broadside crashes were identified to evaluate intersection related crashes. 274 approach and broadside crashes occurred, with the average speed of vehicle one of 25 mph. 98 (35.8%) of these crashes resulted in an injury. The average speed of the injury approach and broadside crashes was 28 mph. Approach and broadside crashes were most common at Mississippi Avenue and C-470.

Figure 5: Santa Fe Crash History by Crash Type

Implementation and Next Steps

So far in this paper, several suggested alternative potentials were evaluated in the context of existing national projects and operational analysis. Many of the suggestions are design and operational features that would be put in place once final design and construction are complete. Consideration of a viable alternative will combine many of the features mentioned throughout this paper, but should also consider some logical and assumed steps up to and including construction. Once a final alternative is determined, incremental steps toward that alternative can provide benefits sooner than waiting for final construction of the alternative. **Table 10** presents some suggestions for ways in which Santa Fe Drive can be improved prior to full implementation of each alternative.

Table 10 – Incremental Steps Leading to Alternative Construction

Alternative	Incremental Steps
Alternative 1- Maintaining the HOV lane with design adjustments to improve operations and safety	-Conduct safety study and determine if designated HOV lane ingress/egress locations would provide benefit compared to the current continuous access provided. -If designated ingress/egress zones are established, consider locations where existing ROW would allow for installation of a striped buffer between general traffic and HOV lanes. -Upgrade ITS technology along the corridor including a complete fiber optic backbone and continuous CCTV coverage to allow CDOT to better monitor conditions along the corridor. -Provide additional dynamic message signing including travel times for the HOV lane compared to general traffic to encourage carpooling. -Consider ITS technologies for enforcement to improve compliance.
Alternative 2- Conversion of existing HOV lane to a general-purpose lane	-Determine if legislation prevents conversion of HOV to general-purpose lanes.
Alternative 3- Relocation of the HOV lane from the left lane to the right lane to avoid left turn weave conflicts	-This alternative does not lend itself to incremental steps; full adoption would need to be completed to see potential benefits along the corridor.
Alternative 4- Enhanced at-grade managed lanes from C-470 to I-25	-Determine CMAQ funding used previously on Santa Fe Drive and legal barriers that may exist. -Perform incremental steps noted under Alternative 1.
Alternative 5- Enhanced managed lanes from C-470 to I-25 including grade separation at major intersections	-Determine CMAQ funding used previously on Santa Fe Drive and legal barriers that may exist. -Perform incremental steps noted under Alternative 1. -Determine optimal ingress/egress locations, taking into consideration Santa Fe Drive access points and future fly-over locations. Modify portions of corridor that may not have fly-over ramps constructed to improve safety.

Construction

The resources required and invasiveness of each alternative will likely play a role in narrowing down suitable solutions. Final construction of each alternative will apply many of the design features and operational requirements laid out in previous sections. It would also need to consider right-of-way along the corridor. A general and broad evaluation of the challenges each alternative faces in relation to construction can be inferred from the previous research and alternative descriptions.

Alternative 1, Alternative 2, and Alternative 3 would likely require restriping and signage installation and could be implemented at a relatively low construction cost. Some widening may be beneficial to provide buffers or additional shoulder space if it is deemed necessary. Alternative 1 may also benefit from construction of facilities that separate left turns from HOV lanes. For example, jug-handles could be considered to remove the need for vehicles to enter the HOV lane to access their intended direction. Quad roads could also provide drivers additional separation from the HOV lanes and still be able to reach intended destinations. Each of these three alternatives would not require any tolling infrastructure and likely only use limited ITS infrastructure.

Alternative 4, in order to produce a safer and efficient HOT facility, would likely need some widening at locations to allow for buffer zones and specific ingress/egress locations. In addition, installation of tolling infrastructure would be a large part of the construction process. Construction would also be impacted by any subsequent changes made to surrounding roadways, additions of quad roads, or changes in intersection geometry.

Alternative 5 would likely require the most effort during the construction phase. In addition to sharing several aspects of Alternative 4 such as tolling infrastructure, widening and potential changes to surrounding facilities, Alternative 5 would also require installation of fly over ramps. While these are expected to offer the greatest benefit to HOV lane users, they would also be the most costly aspect of any of the alternatives.

Conclusion

There are many challenges and characteristics that should be reviewed when evaluating solutions to the issues facing the HOV lanes on Santa Fe Drive. This paper has attempted to condense information, strategies, suggested alternatives, and analysis that could be considered to arrive at a solution and provide feedback on managed lane strategies. Each alternative has its benefits and drawbacks based on the various aspects of HOV and HOT lane design and operation discussed in this paper. Below is a summary of potential benefits and barriers for each alternative based on the contents included in this paper.

Alternative 1 may be one of the lowest cost ways to improve HOV operations and safety along the corridor without the need for major reconfiguration of Santa Fe Drive. The alternative could utilize a number of strategies discussed in the national research section including: allowing electric vehicles free access to the lane, increasing the buffer zone to improve safety, modifying left turns and geometry at intersections, and reevaluation of ingress and egress strategies along key points of the corridor. There are unlikely to be any legal constraints for this alternative. Construction would be minimal, though it is likely safety improvements would also be minimal when compared to other alternatives.

Alternative 2 would remove the need for enforcement and, subsequently, violations would no longer be an issue. Research shows promising potential for improvements to operations and air quality. Construction and cost would likely be limited to restriping and some widening in key areas. Removal of the HOV lane may also improve safety by reducing the need for drivers to cross over the HOV lane to access left turn lanes. However, converting HOV lanes to general-purpose requires legislative action and removes the potential for CDOT to dynamically manage demand on the corridor.

Alternative 3 moves HOV lanes from the left lane to the right lane and would remove the need for vehicles entering the roadway to cross multiple lanes to reach the HOV lane. However, it would require vehicles entering the roadway to move out of the HOV lane or risk violations. Construction and cost would be minimal and would likely only require restriping and signage replacement. Legal barriers are not likely to be an issue with this alternative. This strategy would offer police officers vantage points from which to look for violators. Safety would likely continue to be an issue for this alternative as weaving across the lane to access right turn lanes and driveways offer potential conflict areas.

Alternative 4 introduces a managed lane approach to the current facility. Minor design changes such as larger buffers and roadway widening should be considered; however, construction would be significant with adding tolling facilities and managing ingress and egress locations. Costs would likely be higher than other non-managed lane alternatives, but that may be offset by tolling revenue. Operational improvements for those utilizing the managed lane may not be significant considering the at-grade nature of the HOV lanes and lack of preferential progression at intersections. US Title 23 Code 166 (b)(4) allows this alternative under the condition that specific speed conditions are maintained on the HOV lane, and an enforcement program is in place, which introduces legal considerations during and after construction. It is unclear how interested the public would be in paying tolls if they would still have to stop at traffic signals.

Alternative 5 improves the managed lane approach by separating the HOV lane from traffic at signalized intersections. Construction and costs for this alternative would be high in order to implement fly over ramps. Tolling, ingress, and egress could be strategically placed to ensure anyone using the fly over ramps or HOV lanes are tolled without concern for vehicles that are targeting left turn movements. It is likely this strategy would improve operations as vehicles could avoid delay at specific intersections and demand could be managed through congestion pricing. Like Alternative 4, this alternative would require corridor monitoring to ensure speed compliance under US Title 23 Code 166 (d)(1-2) and specific enforcement program introduction.

Table 11 provides a high level comparison of each alternative and the related aspects considered in this discussion based on safety, cost, operations, legislative issues, and an overall assumption of how difficult each alternative would be to construct. Moving forward, these characteristics and alternatives could form the basis for future decision making.

Table 11. Characteristic Comparison of Santa Fe Drive Suggested Alternatives

Alternative	Safety Benefit	Cost	Operations	Legal Barriers	Ease of Construction
1-HOV Left Lane	Moderate	Lowest	Low	None	Easy
2-GP	Moderate	Lowest	High	Highest	Easy
3-HOV Right Lane	Adverse	Lowest	Low	None	Easy
4-HOT At-Grade	Moderate	Low	Low	Moderate	Difficult
5-HOT Grade Separated	Significant	Highest	Highest	Minimal	Most Difficult

Least Desirable ⟷ *Most Desirable*

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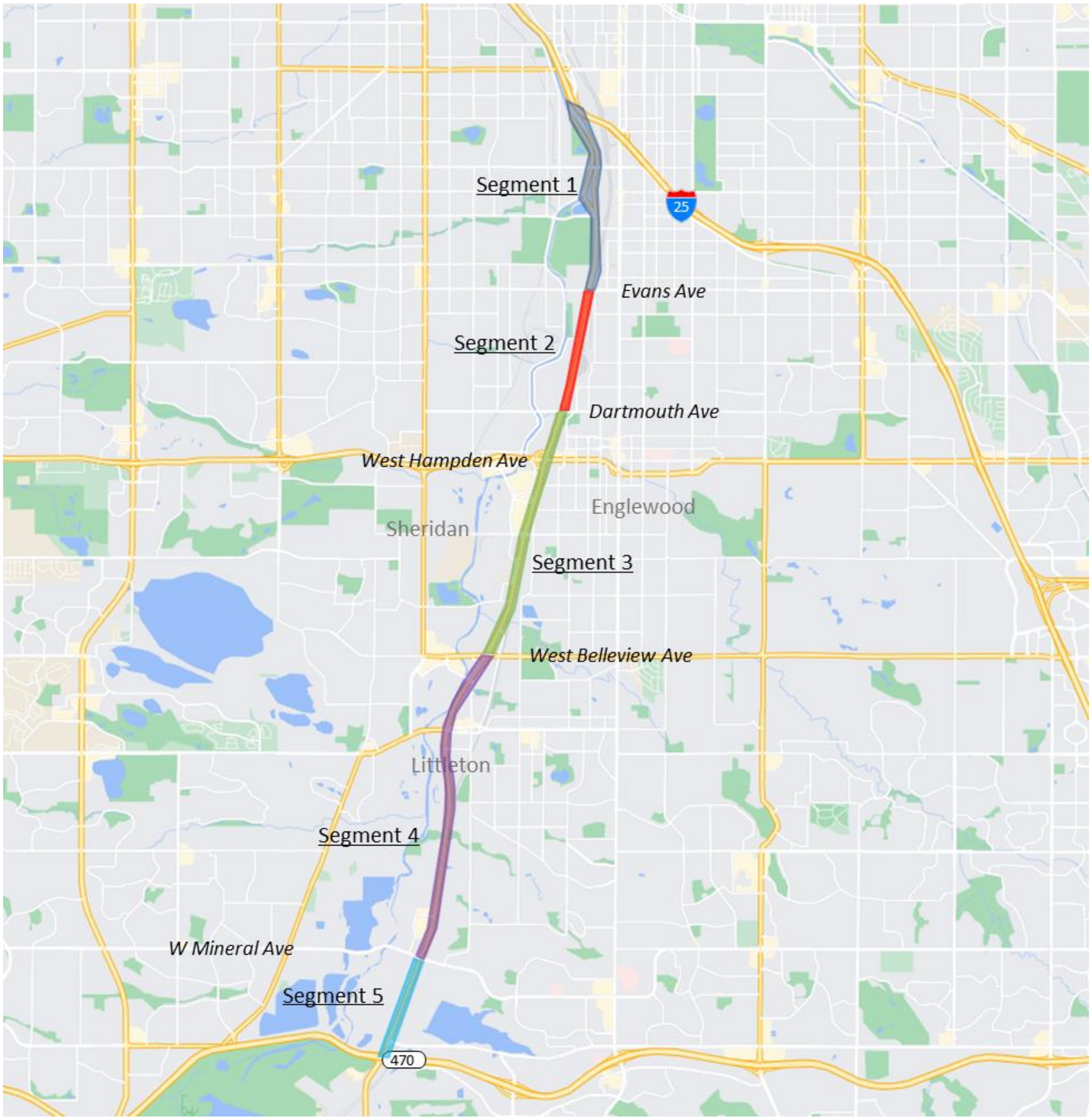
APPENDIX I – POET-ML Analysis Segments



Attachment B. ITS WHITE PAPER

Santa Fe PEL
C-470 to I-25

INTELLIGENT TRANSPORTATION SYSTEMS WHITE PAPER: TECHNOLOGY AND STRATEGIES FOR SANTA FE DRIVE

December 15, 2021

Purpose

This paper evaluates various ITS technologies and strategies that are being considered for implementation on Santa Fe Drive (US 85). The topics covered include:

- Traffic Operations Centers
- Enhanced Communications Infrastructure
- Incident Management Plans
- Improved Traveler Information Signs
- Queue Warning Systems
- Variable Speed Limit Signs
- Wayfinding Apps
- Enhanced Pedestrian Detection
- Enhanced Pavement Markings
- Corridor Signal Timing and Systems Improvements
- Automated Traffic Signal Performance Measures
- Adaptive Traffic Signal Control

Each topic has their own section which presents a summary followed by current practice, examples, and benefits of each. This is followed by a discussion of each topic as it relates to Santa Fe Drive and how easy it might be to implement (including locations and challenges), the compatibility of each technology with existing infrastructure and other planned ITS technology, and the high level cost estimates of each. Finally, information is summarized and ranked for easy comparison.

Introduction

The portion of Santa Fe Drive considered in this paper runs between I-25 and C-470. The corridor is often used as a connection between these freeways, which contributes to high congestion, travel times, and makes it particularly susceptible to incidents on all three facilities. A HOV lane runs in the left lane along much of the corridor, adding complexity to these issues. Many ITS technologies are already in place along the corridor to aid in maintaining operations and monitoring conditions including closed circuit television (CCTV), microwave vehicle radar detection, and travel time index sensors. These are connected to traffic operation centers via an existing fiber optics backbone. To reinforce the corridor and provide a more robust ITS infrastructure to aid in monitoring and maintaining operations, several ITS technologies may be used to provide benefits for Santa Fe Drive, which are further discussed throughout this paper.

Traffic Operations Center (TOCs)

Overview

TOCs (also referred to as Traffic Management Centers [TMCs]) are facilities used by trained personnel to monitor a wide variety of field deployed technologies that track traffic patterns, incidents, and conditions. A TOC's objective is primarily to promote efficient movement of traffic within their regions and areas through the use of data collection and ITS technologies [1]. TOCs can cover a wide range of responsibilities, technologies, and operations which will often include monitoring daily operations, unplanned incidents, special events, weather conditions, and road work [2]. ITS technology can be utilized to carry out specific actions in response to changing conditions on roadways which might include adjusting variable speed limits, notifying motorists of changing conditions, performing lane management and closures, ramp metering adjustments, updating dynamic message signs, and adjusting tolled lane pricing [3].

Current Practices and Benefits of Traffic Operations Centers

TOCs play a vital role in efficient traffic movement using a systematic approach and can play an important role in safety conditions on roadways during inclement weather, crashes, and roadwork [4]. They act as a hub for regional data and incident monitoring, allowing for concise solutions and responses to the dynamic issues of traffic congestion. Typically, evaluation of conditions will be done through the use of ITS technologies that gather real-time data from the field. These can include closed circuit television (CCTV), variable message signs (VMS), radio transmitted advisory messages, variable speed limits (VSL), sensors (such as microwave vehicle radar detectors, induction loop sensors, infra-red light sensors, and lidar traffic sensors), and central traffic signal systems and software [3]. If an accident occurs, the proper emergency response personnel can be alerted. Tow-trucks and cleanup crews can be directed to an incident to quickly clear debris or disabled vehicles allowing for traffic flow to return. Issues with traffic signal timing and coordination in the field can be monitored and quickly repaired. Additionally, TOC operators can alert motorists to closures and alternate routes in near real-time through variable message signs (VMS), radio transmitted advisory messages, and other methods. The actions to mitigate incidents that TOCs handle have shown to directly improve freeway speeds and delay [5]. Mitigation of these traffic incidents is, therefore, a highly cost effective strategy due to the economic costs of stopped traffic and accidents. This makes them valuable assets for regions, areas, and corridors that experience frequent congestion. Figure 1 outlines some of the typical elements that comprise a ITS network, and shows how each aspect might be connected to a central TOC.

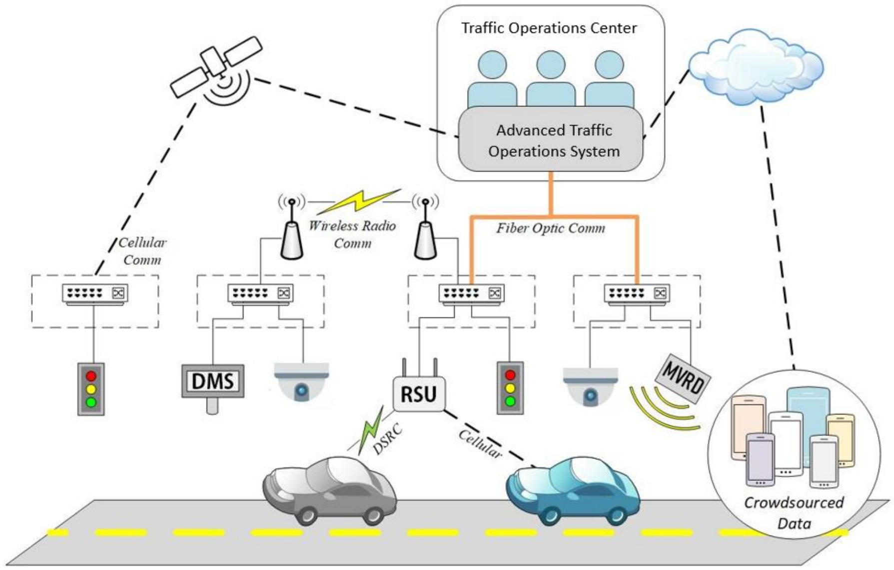


Figure 1. Typical High-level ITS Network Architecture

TOCs are currently utilized extensively across the United States. Multiple TOCs can be located in a single state based on the needs of metropolitan areas and high traffic corridors [4]. They can be serviced by county, city, state, and district DOTs, or a combination of these, though they can also be contracted out to private entities [4] [6]. Some of the most common applications of TOCs identified in a national survey include: network surveillance, roadway closure management, traffic signal control, traffic probe surveillance, traffic metering, portable work zone ITS systems, variable speed limits, high occupancy vehicle lane management, high occupancy toll lanes, and reversible lane management [4]. These applications utilize many of the technologies covered throughout this paper to alleviate congestion and warn motorists of roadway issues. Efficient and timely communication between TOC operators and motorists is also important to the transportation system. In the same survey, the most common traveler information applications included dynamic message signs, traveler information websites, emails and text alerts, 511 systems, social media, highway advisory radio, and third party/automated data feeds [4]. It should be noted that 511 systems, and likely highway advisory radio transmissions, may be underutilized by travelers due to the prevalence and availability of travel apps [3]. Regardless, most of these communication options are utilized by TOCs in some way.

Control rooms at TOCs can vary widely in size, staffing, and technologies utilized. Typically, TOCs include numerous skilled operators who monitor conditions on several monitors, sometimes mounted to the facilities' walls [3]. The importance of trained operators in TOCs is cited by many agencies as an integral part of a well performing facility [3] [4]. In addition to monitoring conditions via CCTV cameras, TOCs can be responsible for hundreds of traffic signals and keep a watch for possible signal issues and equipment outages on their corridor. Fiber optics and internet connections play an integral role in communications between the TOC and traffic signals [3]. Fiber optics and communications also allows for data sharing between agencies and collaboration between multiple facilities. Data can also be collected from external sources including CCTV (those not directly under TOC observation), 911 calls, weather forecasting and road weather conditions, freeway traffic data, traffic probe data (Bluetooth, license plate, etc), arterial traffic or signal timing data, and GPS data [4]. Additionally, collaboration between agencies and sharing of data can provide additional benefits of the ITS infrastructure by synergizing data, CCTV video, and signal information between different agencies and portions of the corridor.

TOCs utilize an array of ITS technologies and take on many responsibilities related to traffic management. The benefits to having a well-integrated and functional TOC are as diverse as these technologies and responsibilities. Some of the most influential of these benefits include:

- Active monitoring of corridor conditions
- Deployment of incident response in real-time
- Ability to actively send alerts to motorists
- Improve travel times and speeds

TOCs and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Further Implementation

++++ - Several TOCs exist throughout Colorado including TOCs at Golden (Colorado Transportation Management Center [CTMS]), Eisenhower Johnson Memorial Tunnel, Hanging Lake Tunnels, and in Pueblo [7]. Existing fiber optics exist along portions of Santa Fe Drive, and many ITS devices are already in place. This fiber optic system and ITS infrastructure is currently handled by the CTMC. Most upgrades associated with ITS technologies and strategies would require a TOC, making the presence of the CTMC an important asset in equipping the corridor with additional equipment.

Communication between the City and County of Denver (CCD) and the Colorado Department of Transportation (CDOT) could offer benefits by sharing arterial and mainline coverage and issues. This could be used to develop more efficient rerouting plans and broadcasting of congestion issues along the corridor to other potential ITS technologies such as VMS, queue warning, and VSL. While center-to-center (C2C) communication between CCD and CDOT already exists, collaboration between agencies goes a long way in making congestion management and mitigation more effective. Sharing information in regards to signal conditions, CCTV footage, and traffic conditions could help in incident and emergency response. In particular CCTV footage can be utilized by all parties involved in monitoring the corridor for expedient and efficient reactions to incidents, improving incident response, and clearing accidents to restore traffic conditions. Planning and discussions around the alternative designs and considerations for improvements along Santa Fe Drive offer a unique opportunity to combine new ITS infrastructure, TOC responsibilities, and increased C2C. In particular, managed lane alternatives for Santa Fe Drive would require improvements and additions to Santa Fe Drive and the CTMC. Monitoring conditions and communicating potential price adjustments for Santa Fe Drive from CTMC would require enhanced connectivity and ITS technologies. While there are costs from building, monitoring, and maintaining managed lanes from the CTMC, the price could be offset to a degree by the revenue brought in from tolls.

Compatibility with Other ITS Technologies

++++ - The issues of congestion along Santa Fe Drive provide opportunity for improvements through the use of congestion mitigation and ITS technologies. Potential improvements include covering any existing gaps in CCTV coverage, extending fiber optics along the remaining portion of Santa Fe Drive, traffic signal monitoring, and intra-agency communication and cooperation between arterial and mainline monitoring.

A TOC would also be responsible for operating any new technologies added to Santa Fe Drive including variable message signs, variable speed limit signs, and queue warning signs. The TOC would be the central location utilizing all these technologies and strategies.

Costs

$ - Because the CTMC is already utilized to monitor and manage traffic on Santa Fe Drive, there likely wouldn't be significant costs associated with TOC upgrades for the corridor. Additional CCTV camera sites could cost up to $100,000 per site including infrastructure. Costs for other technology deployments that could be integrated with a TOC are noted in subsequent sections. There is a chance that additional TOC personnel would be required if new monitoring/management requirements associated with such deployments exceeded the capacity of the existing workforce.

Enhanced Communications Infrastructure

Introduction

Communications infrastructure is essential to an ITS network as it allows devices to act in concert, and allows a path through which collected data can be transferred to central servers and system operators. Communications reliability plays a strong role in the effectiveness of an ITS network. Most transportation agencies utilize some combination of cellular, wireless radios, and fiber optics within their communications networks. Each of these technologies has relative strengths and weaknesses, many of which are outlined in Table 1. Where fiber optic infrastructure is practical, it is typically preferred due to its high reliability and bandwidth capacity. This is especially true for data-intensive applications such as video streaming.

Table 1 – Typical ITS Communication Technologies

Communication Type	Initial Cost to Deploy	Cost to Maintain	Expertise Required to Maintain	Bandwidth	Reliability	Additional Considerations
Fiber Optic	High[a]	Low[a]	High[a]	High	High	Reliability is increased when redundant communication pathways exist.
Wireless Radio	Low	Low	Medium	Low	Low	Typically must be backhauled using other communication methods.
Cellular	Low	Medium	Low	Medium	Medium	Requires subscription from wireless provider. Often deployed in remote areas where fiber is not cost effective.

a) Assumes agency owned fiber. Agencies can also be shared among agencies or purchase subscriptions through internet service providers to provide communication.

Current Practices and Benefits of Communications Infrastructure

Many agencies and transportation departments continually deploy increasingly expansive fiber optic networks due to the high bandwidth and reliability these networks provide. Many larger agencies such as CDOT and the City & County of Denver have been building out their networks for many years, and have many miles of existing fiber optic cable covering a large portion of the major roadways within their boundaries. Fiber optic technology is relatively mature and well understood, and these larger agencies often have the knowledge and expertise in-house to adequately operate and maintain these large networks.

The data throughput capabilities of fiber are notably higher than other communications media, but the amount of data that can be transmitted is still limited by the number of fiber optic strands within the fiber optic cable. Typical “backbone” cables may include between 48 and 216 strands, with the higher strand counts providing greater throughput capacity and the ability to dedicate fiber strands for a variety of purposes. In locations where fiber strands are at a premium, there are technologies that can improve capacity by allowing more data to be transmitted over a single fiber strand. For example, CDOT uses coarse wavelength division multiplexing (CWDM) in some locations to transmit as many as 10 separate communications signals of different wavelengths on a single fiber strand; effectively multiplying the capacity of their network. The tradeoff for this increased efficiency is that the equipment necessary for CWDM is more expensive than standard fiber deployments, meaning that the technology is typically best utilized in locations where fiber strands are at a premium. Dense wavelength division multiplexing (DWDM) allows for even greater throughput than CWDM, but even higher equipment costs makes it impractical for most ITS applications.

It is common for agencies to share their fiber optic infrastructure with other agencies through trades or leasing agreements to receive additional value from their existing infrastructure and reduce the need for new construction in locations where existing fiber has already been deployed. The City of Littleton, for example, currently uses strands of CDOT’s fiber backbone along Santa Fe Drive for communication to the traffic signals on the corridor that they operate and maintain. This allows Littleton the benefits of fiber communications to those locations without the high cost of deploying new fiber.

In some cases, local agencies can also lease fiber optic strands to other groups that can benefit from the infrastructure. The City of Centennial has deployed an extensive fiber optic network throughout their city limits, including a 432 strand cable in many locations. The City leases strands of this “Fiberworks” cable to telecom companies and other private groups, ultimately receiving monetary value in return for their initial infrastructure investment. To enable such a strategy, it was necessary for Centennial to hold a public vote to opt out of Senate Bill 152, which restricts government agencies from competing in the telecom space. Any Colorado agency aiming to lease their fiber infrastructure to private companies would also first need to pass a similar public vote.

While fiber is less susceptible to signal interruption than other communications media, the potential still exists for communications disruptions due to cut cables or equipment failure. For this reason, redundant communications pathways are preferred for critical communications links. Ideally this involves a completely separate physical pathway from the signal origin to the backhaul location. Where possible, it is advisable to deploy a ring or mesh topology to enable such alternate pathways for signal transmission.

While still inferior to fiber in terms of bandwidth and reliability, the capabilities of wireless radios have improved in recent years. While traditional narrow band radios in the 900 MHz range typically struggle with high-throughput applications such as video streaming, broadband radios that operate in the 2.8GHz and 5.8GHz ranges are often adequate to backhaul video streams from multiple field locations; provided adequate line-of-sight exists between the respective antenna locations. Because all of these radio types operate over unlicensed frequencies though, they can encounter interference from other radio sources that commonly exist in urban environments. The potential for signal interruption due to interference or physical obstructions makes radio communication most practical in locations where a temporary signal interruption is acceptable.

The overall benefits of a strong enhanced communications structure include:

- High bandwidth, reliable connections to ITS devices, and redundant communications to traffic signals and other equipment
- Important enabler of other ITS technologies

Communications Infrastructure and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

++++ - As shown in Figure 2, there is an existing CDOT 48 strand fiber optic cable from Dartmouth Avenue through the southern limits of the study corridor. All of the traffic signals and CDOT ITS devices within this range currently communicate via this backbone. Because this backbone terminates at Dartmouth Avenue, there is no redundant communications pathway, leaving the connected devices susceptible to communications outages due to fiber optic cuts or upstream equipment failures. While there is no CDOT fiber between Dartmouth Avenue and I-25, there are CCD fiber optic cables that cross the corridor at each signalized intersection within the study limits. All traffic signals at these locations communicate via these backbones. Between these intersections, there is no other known agency fiber.

At any location where one agency wished to utilize existing fiber of another agency though, it would be necessary to coordinate with that agency to enable the use of their infrastructure, and to organize a method to backhaul those signals to the appropriate central server location; potentially via a center-to-center connection, or by splicing together the agencies' fiber at a separate location where their respective backbones are in close proximity. That said, if a CDOT managed ITS solution were to be deployed along the north portion of the study corridor, it may be preferable to simply extend the existing fiber optic backbone north to connect to the existing CDOT backbone on I-25. This would also improve the reliability and resiliency of CDOT's fiber on the corridor by creating a redundant path for backhauling the communications signal.

Compatibility with Other ITS Technologies

++++ - The existence of fiber optic cables, and the fact that all of the traffic signal controllers on the corridor are already connected to fiber, is an important enabler of future ITS solutions. Devices deployed anywhere south of Dartmouth Avenue, or at signalized intersections to the north, could presumably communicate via this existing infrastructure. New fiber optic cables north of Dartmouth would allow for ITS solutions to be deployed along the entire corridor between I-25 and C4-70, also completing fiber optic connection between these two highways.

Costs

$$$$ - The cost to extend the existing CDOT backbone from Dartmouth Avenue to I-25 would be approximately $825,000. If it was determined that the existing 48 strand backbone was inadequate for future applications, the cost to install a larger backbone between C-470 and Dartmouth Avenue would be approximately $350,000.

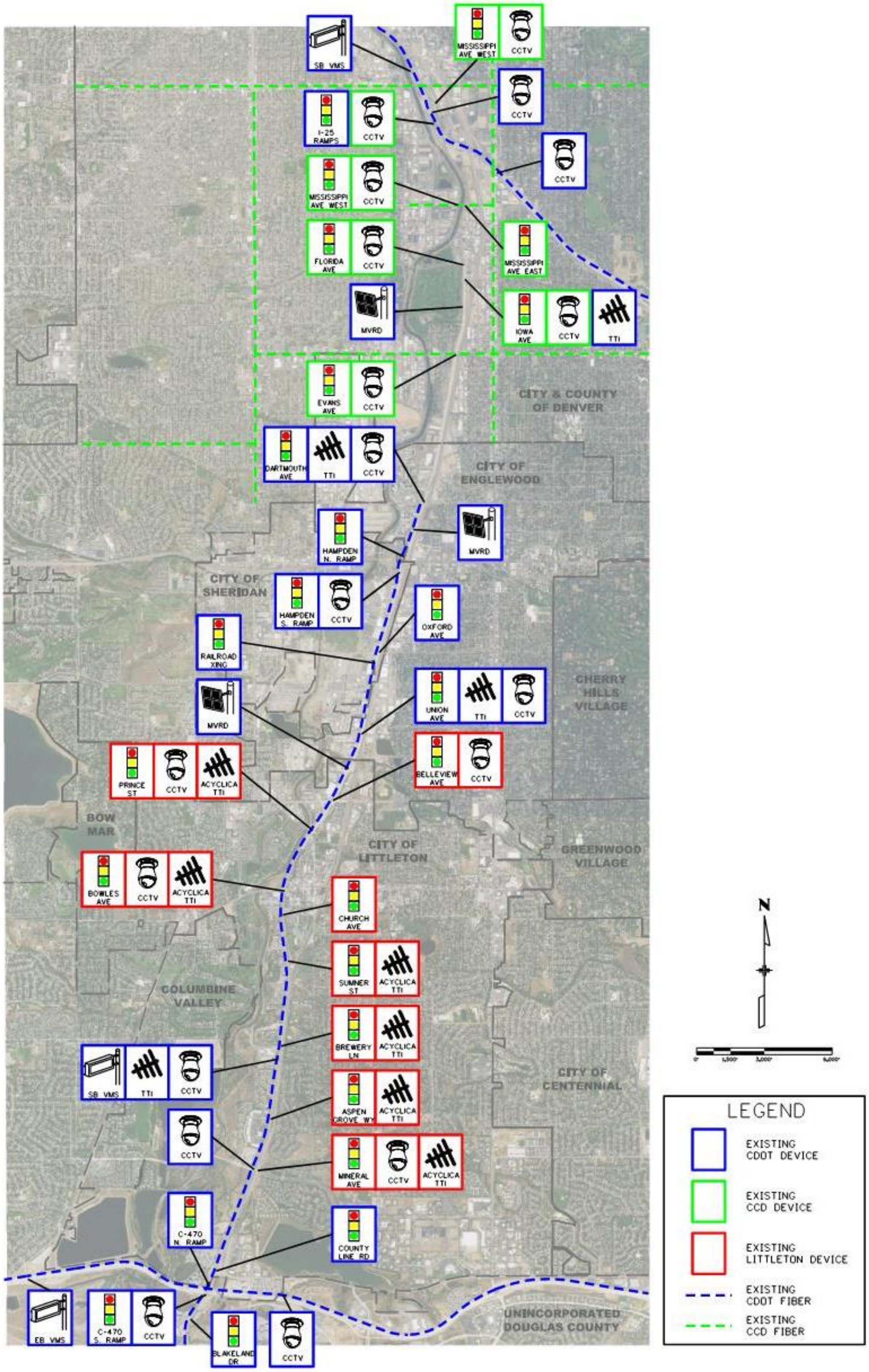


Figure 2. ITS and Fiber Optic Network along US 85 (Santa Fe Drive)

Incident Management Plans

Overview

Incident Management Plans (IMPs) are a strategic set of actions that are followed across multiple agencies and disciplines in reaction to traffic incidents in order to restore traffic flow quickly, safely, and efficiently [8]. Traffic incidents can cause safety issues for both motorists and emergency response personnel and can cause serious traffic delays. Rapid and organized responses are vital to quick and safe cleanups. Agency response to an incident and responsibility to lead the response depends on the jurisdiction, or jurisdictions, in which the incident occurred. Therefore, it is important to have a well laid out and understandable plan to handle these situations and inform different parties of what one another's responsibilities may be and who they will be answering to.

Current Practices and Benefits of Incident Management Plans

The importance of a well-organized IMP has been recognized for some time, and the National Traffic Incident Management (TIM) Coalition along with other government agencies and representatives has set up the National Unified Goal as a means to help transportation agencies develop appropriate and effective goals and objectives for incident management programs [9]. To aid in TIM program evaluation, the FHWA also developed the Capability Maturity Self-Assessment which provides guidance for improving areas of TIM programs [10]. The most common strategies employed by agencies around the United States include incident detection and verification by first responders, traveler information (511 systems and dynamic message signs), incident response (computer aided dispatch, towing, etc.), scene management and pre-determined command structures, traffic control, and debris and vehicle clearance/recovery [11]. Tools typically used to address IMP issues include improved agency relations and communication, personnel training, implementing appropriate technology, collecting and analyzing performance measurements, and program resources and funding [11].

In practice, an IMP will begin with detection of incidents, which may originate with first-responders, non-responders, or the public. The subsequent actions and delegation of resources and sharing of information will occur via a communication center of the agency receiving incident information, whether that is a TOC or dispatch center, which then relay information and deploy necessary resources as per standard procedures and Incident Command [12]. Law enforcement, fire and rescue, towing, hazmat teams, medical examiners, dispatchers, and DOTs can all be involved in the strategies and responsibilities in reacting to traffic incidents, and their cooperation is key to the execution of an IMP [13].

DOTs and ITS technologies play a vital role in how information is received and shared within an IMP. Resources and technologies that may be utilized by transportation agencies in include CCTV cameras, 511 lines, and variable message signs [12]. Maryland's Department of Transportation Coordinated Highways Action Response Team (CHART) utilizes many unique strategies and technologies and is often cited when quantifying benefits of traffic incident response and management programs [13] [14]. They utilize patrols, traffic operation centers for central condition and data observations, CCTV, microwave traffic flow sensors, weather stations, dynamic message signs, snow emergency plans, event mapping, work and lane closure permitting, publicly available GIS incident mapping, highway advisory radio, and 511 services [15]. CHART and its patrols work together with several other agencies including the Maryland Highway Administration, Maryland DOT, Maryland Transportation Authority, and the Maryland State Police [16].

Another example is Florida's traffic incident management program which has been around for over thirty years. Technologies utilized by Florida's TIM program include dynamic message signs, regional and satellite transportation management centers, and advanced traffic management system (ATMS) software. They were one of the first to implement state police computer aided dispatch and have a large fleet of service patrols to aid in incident response and cleanup. Structurally, FDOT utilizes a hierarchy with a state wide program manager and TIM working group (which includes almost 15 separate organization and agencies), district program managers, and 25 local teams (which include representatives from law enforcement, fire/rescue, EMS, towing, and transportation).

Agencies will often track performance measures to evaluate the impacts newly implemented strategies, tools, or organizational structures have on a traffic incident management plan or program. This analysis allows well documented benefits of IMPs which can include [14] [17]:

- Reduction in delay due to traffic incidents
- Avoids rerouting and unplanned detours
- Economic savings from reduced delay and improved safety for drivers
- Improved safety of incident responders
- Reduction of secondary crashes

IMPs and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

+ - In Colorado, traffic incident management teams are broken down into the Northeast Region, Southeast Region, Southwest Region, Northwest Region, and the Metro Region. The Metro Region team is further broken into the West Denver, South Denver/Castle Rock, East Denver, and West Denver Metro TIM teams [18]. Santa Fe Drive traffic incident management would currently fall under the South Denver/Castle Rock Metro TIM Team and is monitored by the CTMC. Responding agencies on Santa Fe Drive include CDOT, Douglas County SO, Colorado State Police, Littleton Police Department, Englewood Police Department, and South Metro Fire. Communication between agencies in Colorado that are responding to incidents is carried out via center console-to-console networks and WebEOC, which allows first responders to relay information quickly and efficiently [12]. Twenty-three separate TIMP documents exist for corridors throughout the state. However, there is not a specific TIMP for Santa Fe Drive. Developing a unique TIMP for Santa Fe Drive would require a lot of resource allocation for such a short corridor and may be redundant based on existing incident management teams and their respective response areas. Consideration should be given to including Santa Fe Drive response in existing plans rather than to create its own separate TIMP.

Compatibility with Other ITS Technologies

+++ - Utilization of several ITS technologies in incident response is already a well-established and useful strategy in IMPs. CCTV, center-to-center communications, dynamic message signs, and traffic signal monitoring can all be used in incident management plans and response. So long as a specific technology exists on the corridor, it has potential for implementation into an IMP.

Costs

$$ - The costs associated with an IMP and Santa Fe Drive would either require integration of the corridor in another plan, or its own separate plan. Training of new personnel would likely be required if new ITS technologies were deployed and used in incident management and response.

Improved Traveler Information Signs

Overview

Traveler information signs can serve a wide variety of purposes by providing motorists with traffic related updates. A common strategy for relaying this information to travelers include variable message signs (VMS, also called dynamic message signs or changeable message signs) that can display important information that needs to be conveyed to travelers. These can be portable or permanent and are typically placed in strategic locations (such as upstream of important wayfinding and decision points) to help motorists make safe and well informed travel decisions.

Current Practices and Benefits of Improved Traveler Information Signs

VMS are a mature technology with a long history of transportation applications and are used on both freeways and arterials. As of 2002, there were already 2,744 permanent VMSs deployed on roadways in the United States [19]. Standards and guidance for VMSs is included in the Manual on Uniform Traffic Control Devices (MUTCD). Messages on VMSs can be changed by TOC operators monitoring conditions using CCTV on the roadway, but can also be set to change based on corridor conditions and sensor feedback. Due to the nature of VMSs and their role in warning motorists of conditions or changes downstream, placement of any permanent VMS is typically done upstream of potential issues.

There are a variety of opinions on how frequently messages should be shown to motorists via VMS. Showing VMS messages constantly could potentially lead to apathy towards messages. On the other hand, showing messages infrequently is avoided by some agencies to prevent motorists from feeling the sign is a waste of money or is not functioning [20]. Types of messages allowed varies by state. While some agencies specifically target traffic related messages, others allow public service announcements, seatbelt reminders, and other non-urgent reminders [20]. Specific message types displayed on VMSs can include incidents, lane closures, travel times, congestions management, air quality, special events, safety messages, alternative routes, enforcement actions, and emergency messaging [20]. Prohibited messages can include advertisements, dates and time, general weather information, and animations [20]. Currently, CDOT's policy for displaying messages on VMSs is to follow MUTCD guidelines. The CTMC has authority to change VMS messages statewide remotely, though CDOT Regions can over-ride messages that are being displayed within their areas [21]. Only messages regarding road, weather, construction, and traffic information can be shown on VMS. VMSs exist all over Colorado, however the greatest concentration of these signs is along I70 through the mountains for wildlife, closure, congestion, incident, and weather conditions.

A recent large scale example of variable message signage is the completion of project NEON ATM system in Nevada on I-15 and US-95. The project is a collaboration between the Regional Transportation Commission of Southern Nevada who operates the system, Nevada Department of Transportation who owns the equipment, and Kimley-Horn who owns the software [22]. This system incorporates 42 signs including traffic incident messaging, lane assignment, ramp metering, and variable speed limits (discussed further in section Variable Speed Limit Systems) as shown in Figure 3 [23]. CDOT has similar installations of ATM corridors along US-36 and North I-25, as well as the future Central 70 corridor that is now under construction. Smaller, lower cots examples of VMSs are often used in urban environments including one southbound on Santa Fe Drive near mile marker 202, just before entering C-470. There are also several examples of lane assignment and information sign examples on I-25 north of Denver between Thornton Parkway and 120th Avenue.

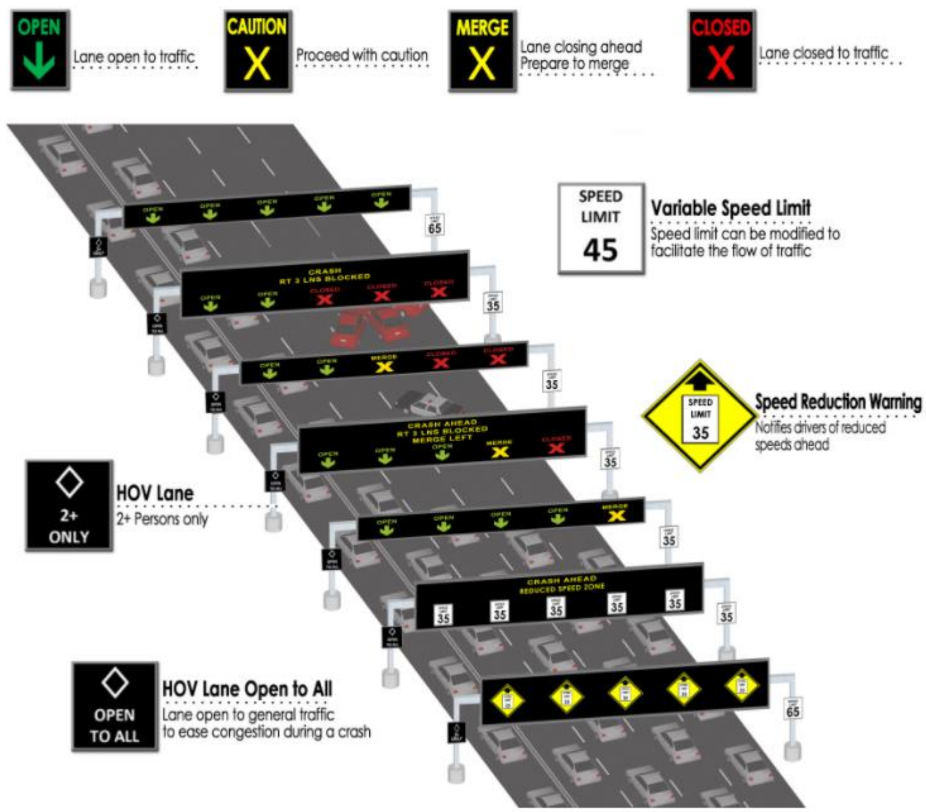


Figure 3. Project NEON ATM Signs [23]

Benefits of VMSs include [24]:

- Ability to convey real-time information to every motorist passing the sign location
- Increased driver situational awareness
- Displays supplemental information for VSLs and queue warning systems

Improved Traveler Signs and Santa Fe Drive: Cost, Upgrades, Updates

Consideration/Practicality of Implementation

++++ - Santa Fe Drive is susceptible to queuing and high travel times due to high demand and numerous signalized intersections. Additionally, inclement weather can be an issue for several months of the year on the corridor. Improved traveler signs such as VMSs can, therefore, be beneficial by providing motorists entering the corridor with information about current conditions. This could include intersections with high queueing, incident locations, travel times, weather updates, and potential construction. This would give motorists time to consider alternate routes or prepare for heavy congestion. Additionally, being shown travel time information could offer incentive for some drivers to consider carpooling or paying a toll (if a toll lane is implemented) as a means to bypass backups on general lanes. The corridor is already equipped with travel time devices along much of the corridor.

VMSs do currently exist southbound on I25 before the Santa Fe Drive exit, southbound on Santa Fe Drive south of Brewery Lane, and eastbound on C-470 prior to the Santa Fe Drive exit, as seen in Figure 2. It could be beneficial to include a VMS for motorists entering Santa Fe Drive northbound via C-470 to inform motorists of travel times on general purpose lanes and HOV lanes. The sign could be located just south of Mineral Ave. Another location could be for those entering Santa Fe Drive southbound via I25, with the sign being placed just north of Mississippi Avenue.

Compatibility with Other ITS Technologies

++++ - VMSs would synergize well with other ITS technologies currently deployed on Santa Fe Drive. While CCTV coverage does not include every portion of the study corridor, the cameras that are deployed can be used to evaluate corridor conditions and determine appropriate messages to display. Roughly two-thirds of the corridor has an existing fiber optic backbone that could be used to establish communications to proposed VMS. If the backbone is not extended, any VMS deployed outside of the limits could communicate via wireless radios or cellular modems. VMSs could also be used in conjunction with VSL and queue warning systems to supplement traffic conditions on the corridor. Drivers may be more compliant with reduced speeds if a message indicates the reason, or displays notifications of the enforceability of variable speeds [24].

Cost

$$ - Costs for VMS will be largely dependent on the infrastructure to build and support them. The cost to deploy a single, standard overhead VMS (similar to the existing sign on Santa Fe Drive south of Brewery Lane) could cost approximately $275,000. Smaller VMSs could cost approximately $175,000.

Queue Warning Systems

Overview

Queue warning systems use sensors to identify when traffic queues or slowdowns are occurring in real time. The information is then displayed on upstream VMS or other dynamic signage to alert motorists that speeds should be reduced. Messages can be updated manually by TOC operators or automatically based on algorithms and software. Such systems are sometimes combined with variable speed limits to further control vehicle speeds and improve driver situational awareness.

Current Practices and Benefits of Queue Warning Systems

Queue warning systems can be placed in a wide range of locations including areas where vision of traffic may be obscured (such as curves, grade, and poor lighting), in areas where stopping is not usually expected (lane closures and work zones), or in areas where queuing frequently occurs [25]. In cases of frequent and consistent queuing, permanent signage can be placed as a strategy to improve safety. Alternatively, portable message signs can be used upstream of work zones to indicate to motorists that traffic may be stopped due to roadwork. Data collected for use in queue warning systems can come from sensors such as inductive loops, roadside speed sensors, remote traffic microwave sensors, or CCTV [26].

Multiple sensors are typically used to estimate the end of queues. Strategies employed for queue warning triggers include real time data and sensor-based criteria that are inputs for software or algorithms, or manually controlled warnings activated from a TOC that is monitoring traffic conditions [25]. Message selection is an important concept for queue warning systems, and over exposure of motorists to warning signs should be avoided, especially if queues do not exist or have already cleared [26]. Both shockwave and queuing (stop-and-go) analysis have been used to develop software that determines when messages are conveyed to drivers [25] [26].

Temporary queue warning systems are common for work zone applications, lane closures, and construction sites through the utilization of portable VMSs and sensors. There are also examples of queue warning systems being utilized to warn drivers of common queue locations on freeways. No permanent queue warning systems on arterials were identified as part of the research for this paper. Examples of queue warning systems in Colorado include US 36 and North I-25, as well as the future Central 70 corridor that is currently under construction.

The Minnesota Department of Transportation implemented two types of queue warning systems in 2014 as part of a project to reduce safety and improve congestion conditions on a freeway segment at fixed and permanent locations [26]. Each of these systems utilized different methods for detecting queues. One system utilized traditional queuing parameters such as consistently slow speeds of vehicles as an indicator of queue formation and danger to motorists. The other system targeted shock-wave events and made use of an algorithm to identify slowdown events that lasted for a brief time but exposed motorists to crash prone conditions. The systems developed allowed messages to be conveyed by lane and utilized software with the option of manual overrides. It was determined that both of these systems can aid in providing steadier speed and traffic conditions with potential to reduce rear end crash frequency [26].

Applications are also being evaluated to connect drivers with real time DOT data to provide queue warnings. A team of researchers from Indiana University-Purdue University Indianapolis worked on a queue warning system for smartphones [27]. Real time traffic and queue data collected from INDOT sensors along I-465 is processed and warnings are sent to the user's phone about queuing areas. The program was tested mainly using driving simulators, but this shows possibility for queue warning systems beyond stationary signs. In the future as connected vehicle on-board units become more widely deployed within vehicles, queue warnings could be transmitted directly to displays inside vehicles.

While queue warning systems can be used in a variety of situations, their benefits are typically the same regardless of deployment reasons. These benefits can include [26]:

- Reduce rear end crashes and secondary crashes
- Warning motorists of queues and reduced speeds
- Speed harmonization
- Improved travel times

Queue Warning Systems and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

+++ - The high incidence of rear end accidents on the study corridor suggests that unexpected queues and slow speeds can be a safety concern for motorists, making queue warning systems a potential ITS solution for specific safety and mobility concerns. While speed sensors can be used to determine queueing, this may pose issues on Santa Fe Drive due largely to the presence of cross roads and traffic signals. These aspects will artificially cause queues and slower speeds at certain locations and it may be difficult to discern these situations from abnormally long queuing. However, if abnormally long queues can be detected within a segment or at a signal, motorists could be alerted and given time to slow down and react.

Queue warning messages could be targeted based on situational circumstances and objectives. For example, warnings of queuing in general purpose lanes may convince motorists that carpooling to utilize the HOV lane may be a solution. Queue warning could also be provided by lane, giving motorists advance notice that a lane they may not need to utilize is backed up, helping to disperse traffic ahead of incidents and queueing. Given the high number of rear-end crashes recorded, the intersections at Dartmouth Avenue, Oxford Avenue, and Mineral Avenue appear to be strong candidates for queue warning system(s). It should be noted, however, that queue warning systems on arterials do not appear to be common. Preliminary studies of the effectiveness of this technology could be conducted using portable queue warning systems to see if safety improves with warnings in place prior to deploying a more expensive permanent queue warning system.

Compatibility with Other ITS Technologies

+++ - Due to the safety hazards of queueing, other ITS technologies could be used in conjunction with queue warning systems to provide further potential safety benefits. VSL (discussed in section below) could be implemented to provide a target speed to motorists as they approach a queue. VMSs could also be provided for additional information such as alternative routes in the case of an incident that causes queuing. As connected vehicle technology becomes more widely deployed, data from vehicles could be used to identify speeds and queuing, and deliver in-cab queue warnings to motorists.

Costs

$$$ - The cost of queue warning systems will be dependent upon a variety of factors including signage type, number of signs, software, system integration, maintenance, installation of infrastructure to support the signs, and the availability of existing sensors. Equipment and infrastructure cost estimates for a new deployment at a single intersection approach range from roughly $175,000 for a static overhead sign with flashing beacons to $450,000 for separate fully dynamic queue warning signs situated over each lane. This technology solution could be useful upstream of any location where unpredictable queues are likely to develop, meaning there could be several separate installation locations along the corridor.

Variable Speed Limit Systems

Overview

Variable speed limit (VSL) systems utilize changeable signage to dynamically adjust speed limits on a corridor in real-time to account for conditions such as congestion, incidents, construction, or inclement weather. The speed limits can be adjusted manually by TOC operators based on observed conditions, automatically based on algorithms that evaluate sensor data, or via a combination of these methods. VSL systems are often supplemented by VMS signs that communicate the causes of reduced speed limits, and are typically combined with other Active Traffic Management (ATM) strategies to further optimize traffic flow [28].

Current Practices and Benefits of Variable Speed Limit Systems

The implementation of VSL systems can be challenging due to the infrastructure investments required and the expertise necessary to calibrate and maintain the system. Project goals for using VSL may include optimizing traffic flow during periods of congestion, improving corridor safety during inclement weather, improving the safety and efficiency of incident response, or a combination of these. These goals and objectives should be considered when determining sign location, how speeds are determined and changed, and Measures of Effectiveness (MOEs) utilized [28]. Depending on the goals selected, an adequate number of weather and/or traffic sensors must be deployed to monitor conditions along the corridor to identify when targeted scenarios occur. Some agencies recommend overhead speed limit signs [28], which further increases infrastructure costs. Power and communication must also be established for each of the system components.

Based on lessons learned from prior VSL implementations that use algorithms to determine posted speeds, Oregon DOT suggests that a qualified professional who understands the VSL algorithm be available for 6 to 12 months after implementation to fine-tune system calibration [28]. It has been noted that dynamically reducing speed limits can cause friction in traffic flow as some motorists adhere to the posted limits, while others continue to travel at faster speeds that are allowed under optimal conditions. This non-compliance has been observed in many VSL system deployments. For these reasons, enforcement is needed to ensure motorists continue to respect the posted speed limits.

The majority of VSL systems in the United States have been established on access controlled freeways. This includes installations on portions of I-70 in Dowd Canyon, West Vail Pass between Genesee and Wadsworth, and Glenwood Canyon in Colorado. These systems are used during inclement weather, congestion events, and construction. Larger VSL deployments nationally include nearly 150 miles of the New Jersey Turnpike used for congestion and weather events, and a large portion of I-285 in Georgia used for congestion issues. There are also successful examples of VSLs deployed on signalized arterials, such as OR-213 in Oregon, but these applications are limited to a single intersection [28]. Some academic studies suggest that safety and operational benefits can be achieved by implementing VSLs along longer stretches of arterials [29], particularly within the context of connected vehicles – but no such systems were found during the course of the research for this paper. This is likely due in part to the complexity of traffic movements on such facilities, the complicated algorithms that would be necessary to appropriately configure the system, and the relative immaturity of the required technologies.

VSL systems can also be used to prescribe differing speed limits for different lanes. This can be particularly beneficial to corridors that include managed lanes, where speed limits within the managed lanes can be raised to increase the appeal of using the lanes. For example, on I-15 in Las Vegas, speed limits are displayed on large overhead VMS, and often show a higher speed limit for HOV/HOT lanes. Additionally, these same signs can be used to warn drivers of downstream lane closures, to display travel times to common destinations, or to provide general safety and routing messages to motorists.

While the reasons for installing VSL systems vary based on project goals and objectives, some of the main benefits from implementing VSL systems can include [28]:

- Potential for reduced crash rates
- Potential for reduced crash severity

- Potential for shorter travel time
- Improved travel time reliability
- Ability to reduce vehicle speeds in inclement weather

Variable Speed Limit Systems and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

+++ - Between 2016 and 2018, more than half of the crashes on the study corridor were rear end collisions. This suggests that there may be some potential to use VSL technology to promote "speed harmonization", in which traffic speeds are reduced in advance of congestion to decrease the likelihood of crashes. For this reason, locations with a high-potential for VSL system deployment may be similar to queue warning systems; that is upstream of high rear end collision intersections such as Dartmouth Avenue, Oxford Avenue, and Mineral Avenue. Further study is necessary to verify the appropriateness of installation at these locations.

Using similar deployments elsewhere as the examples above, such a system could initially be implemented at one or more key intersections where unpredictable queuing or slower traffic is frequently experienced. The benefits of the system could then be evaluated, and expansion of the system throughout the corridor could be further assessed. Either way, the physical infrastructure required to post signs would be required. The existing CDOT fiber optic backbone along the southern portion of the corridor would be an important enabler of a VSL system, but most of the other necessary infrastructure is not yet in place. In addition, trained personnel would be needed to fine-tune the system. A cost/benefit analysis based on a systems engineering approach is necessary to determine whether a VSL system is justified on the corridor, and to verify appropriate locations for installation.

Compatibility with Other ITS Technologies

++ - As it relates to other ITS technologies, VSL may work well in conjunction with VMS and queue warning systems. As discussed in the queue warning section, this provides motorists with both the warning of slowed speeds and a suggested/enforceable speed limit. However, VSL deployments may be further complicated by the implementation of corridor signal timing changes or adaptive traffic signals. Any VSL system, particularly if it extends through more than one traffic signal, must be attuned to the corridor signal timing to ensure that speed changes are not ultimately counterproductive. Posted speeds will ideally allow platoons released from upstream traffic signals to reach downstream signals during periods of green, thereby reducing vehicular delay on the corridor.

Costs

$$$ - The costs of VSL systems would be dependent on the number of units installed, infrastructure to support signage, required sensors, and access to fiber optic infrastructure at the site. Cost of the physical infrastructure necessary for a single VSL site located on the shoulder could be up to $225,000. If a site includes separate overhead VSLs above each travel lane, the cost increases to approximately $450,000. These costs assume that a fiber optic backbone is already deployed at the site. The number of individual sites required would depend on the overall design of the VSL system, and the length of the corridor over which it was deployed. These costs do not include development of any algorithms or system integration efforts, which may prove to be among the more expensive and technically challenging aspects of a VSL deployment on Santa Fe Drive.

Wayfinding Apps

Overview

Wayfinding apps provide motorists and pedestrians with step-by-step instructions for reaching intended destinations. They are widely used for navigating to new locations and for familiar locations alike. In general, these apps are used to find the fastest or most direct route to a location and can provide travel time, congestion issues, and closures. The apps utilize GPS technology.

Current Practices and Benefits of Enhanced Pedestrian Detection

Wayfinding apps and GPS routing have come a long way since the early rollout of the technology. Originally, these applications would determine routing based on GPS and road maps and return a few prime options based on roadway class and travel time [30]. However, with the advent of applications for smartphones, user speeds, travel time, and GPS data could be utilized to provide real time updates of traffic conditions and more efficient routes. This development has been particularly beneficial to motorists, who can now avoid areas of congestion which are notorious for stop and go traffic and rear end collisions. Wayfinding apps, in a way, serve similar purposes as many of the other ITS technologies listed in this paper such as providing queue warning, travel time projections on VMS, and incident messaging.

Wayfinding apps, the services they provide, and the data they use oftentimes incorporate partnerships with transportation agencies. Originally, travel data was collected almost exclusively by public agencies using installed sensors and travel information relayed to motorists via message boards and radio broadcasts. However, the scope and area the data was collected from was limited. Wayfinding apps and the crowdsourced data they collect can cover a broader area and reach areas where agencies might not usually set up traffic sensors such as rural or residential roadways. Incident reports by app users have also been found to be reported faster than DOT reporting [31]. This data is useful for transportation agencies, and partnerships between agencies such as the Port Authority of New York and New Jersey (PANYNJ) which can omit certain roads from rerouting on wayfinding apps [31].

Collaboration between developer and agency can be important to ensure that motorists are getting correct and clear information. Oftentimes, wayfinding apps can create issues during real time rerouting events. Since roadways are designed with a purpose and capacity in mind, automatic reroutes can lead a high number of motorists on paths that were not intended for high volumes, such as residential or school areas [31]. Additionally, agencies such as CDOT have integrated agency knowledge of closures and travel incidents with Google Maps into COtrip, which aims to provide users with information along intended routes [32]. The intentions are to combine this information with step by step routing for a more comprehensive navigation tool. This approach can help mitigate real time rerouting towards closures, construction, and traffic incidents.

In addition to motorists, wayfinding apps can also offer routing options to pedestrians and provide transit information. GPS data can be used to pinpoint locations and estimated arrival times of buses and rail and provide users with this information to better plan trips. Providing reliable information across multiple modes of transportation can give users confidence in trying alternative methods for traveling to their destination. For example, wayfinding apps can provide users with information about driving, walking, or parking at a transit station followed by transit times to specific locations. If additional travel is required, walk times to the final destination can be provided. Combining this with other travel information gives users start to end directions for a wide variety of modes they might be interested in. Additionally, wayfinding apps have been helpful for the visually impaired, who can now use apps and their audio directions to direct them to their destination [33].

While wayfinding apps can present some dilemmas for transportation systems, overall they provide valuable information which help provide benefits including:

- Provide reliable step by step directions
- Provides travel time and travel information
- Provides alternate routes to avoid congestion and traffic
- Collaboration of both crowdsourced data and transportation agency data

Wayfinding Apps and Santa Fe Drive: Cost, Upgrades, and Updates

Ease of Implementation

+++ - Since wayfinding apps are already in use, and CDOT is already collaborating with many developers, it is not difficult to imagine expanding the scope of information that navigation apps cover for Santa Fe Drive. Expansion of COtrip or collaborative efforts with developers could be used to enhance information on the corridor including agency preferred routes, transit and parking information, and pedestrian routes.

Compatibility with Other ITS Technologies

+++ - If an app is used or developed to provide more detailed information for Santa Fe Drive, it is something that could be integrated with other strategies and technologies. Variable speeds, queue warning, travel times, and alternate routes can all potentially be directed straight to a motorist's phone. Existing sensors and CCTV used to collect travel information destined for TOC operations can also be utilized to provide motorists with information, ensuring they are well informed. Care would need to be taken, however, to ensure messages and information provided by other ITS technologies on the corridor does not contradict information provided to drivers.

Cost

$ - With the release of COtrip, there already exists a framework to provide enhanced wayfinding app capabilities for information on Santa Fe Drive. It is assumed that costs will be minimal, though it would depend on what features the app would include and service fees from map providers.

Enhanced Pedestrian Detection

Overview

Enhanced pedestrian detection utilizes sensors to detect activity near crosswalks and traffic signals, including both intersection traffic signals and midblock pedestrian crossings such as HAWK beacons. Activated sensors can put calls in for walk signals without the need for pedestrians to use push buttons. Additionally, sensors can identify if pedestrians are still in the crosswalk area, allowing for phase extensions, signal time adjustments, and warnings to motorists. Typically pedestrian detection is performed using ITS sensors supplemented with algorithms that can identify pedestrians in real-time using collected data. Additionally, this data can be consolidated and used to monitor and study pedestrian movements on the corridor over time.

Current Practices and Benefits of Enhanced Pedestrian Detection

While the pedestrian push button is the standard method for calling a walk phase, often pedestrians do not utilize this strategy [34]. A solution to this issue, and concerns for pedestrian safety, has been developing over the years in the form of enhanced and automated pedestrian detection. A number of sensor types can be utilized to detect pedestrians, including but not limited to: infrared, microwave, pressure mats, laser scanners, video, and thermal sensors [35]. Early systems within the United States in Los Angeles, CA; Phoenix, AZ; and Rochester, NY were evaluated in 2001 that utilized infrared and microwave detection and showed some promise in improving pedestrian crossing compliance [34]. In 2008, San Francisco's PedSafe program installed automatic pedestrian detection at one intersection using video sensing [36]. The detection was meant to extend green times if the detection showed the pedestrian was unlikely to reach the end of the crosswalk before the red signal, however the project noted further research was needed. Studies conducted in 2019 and 2020 found varying degrees of success with thermal and optical sensor ability to accurately determine and cancel pedestrian calls [37] [35]. Advances in sensor and computing technologies have improved the ability to identify and account for such pedestrians in real-time. The algorithms used to parse the data collected from these sensors and to identify pedestrians often utilize machine learning that allows system performance to improve over time.

In practice, enhanced pedestrian detection technology at signalized intersections should be able to detect pedestrians entering a detection zone and determine when a detected pedestrian has left the vicinity. Detection accuracy is important to ensure pedestrians are provided with walk signals when needed, receive extended clearance time when needed, and warning motorists via dynamic signs of impending pedestrian crossings. Issues with accuracy can be based on several factors including equipment, weather, and lighting [37]. Additionally, the ability to cancel a call when pedestrians no longer intend to use a crosswalk is important to avoid unnecessary vehicle delays. Figure 4 shows a rendering of an enhanced pedestrian crossing and the communications between the signal, warning sign, and a connected vehicle.

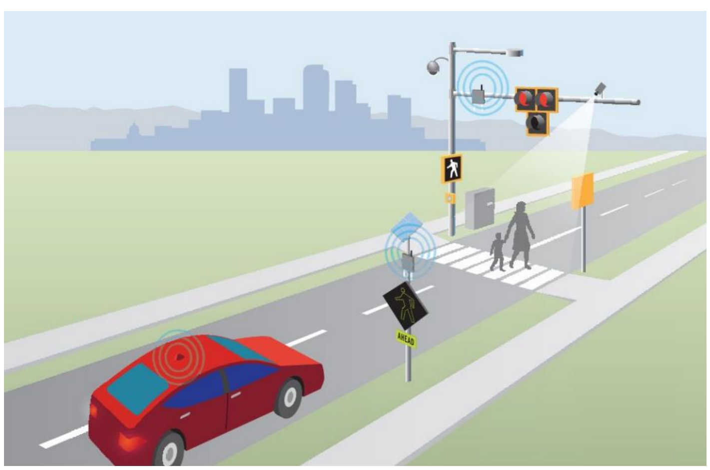


Figure 4. Example of Pedestrian Detection and Advanced Warning

Despite the continued research and need for improvements to detection accuracy, pedestrian safety is a topic many agencies are trying to address and enhanced pedestrian detection technologies and systems continue to be considered and evaluated. The Advanced Transportation and Congestion Management Technologies Deployment Program awarded Denver a grant in 2018 to explore a variety of transportation technologies, including consideration of thermal and optical pedestrian sensors [38]. This program would provide Denver with the only system of its kind. Enhanced pedestrian detection has since been installed at several locations with HAWK signals using video detection in Denver. Video based detection has also been installed at HAWK signals in Boulder with advanced warning signs for motorists. The potential benefits of enhanced pedestrian detection continue to draw attention to the technology. Benefits of utilizing these technologies can include [34]:

- Reduction of pedestrians that start crossing during don't walk symbols
- Reduction in pedestrian/vehicle conflicts
- Increased pedestrian safety

Enhanced Pedestrian Detection and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

++ - Enhanced pedestrian detection is already in place in several locations throughout Denver. However, these are located at HAWK beacon crossings, and Santa Fe Drive has relatively limited pedestrian facilities parallel to the corridor and no midblock crossings. It is unlikely HAWK beacons would be placed on Santa Fe Drive due to the median separated lanes and high volumes. Large gaps in available sidewalks exist, though crosswalks are located at most signalized intersections. Enhanced pedestrian detection should target locations where pedestrian safety at intersections is a key concern. The CDOT Planning and Environmental Linkages (PEL) Study for Santa Fe Drive showed that from 2016 to 2018, there were five recorded pedestrian crashes: two at Mississippi Avenue, one at Iowa Avenue (fatal), one at Evans Avenue, and one at a non-intersection location. In addition, the Colorado Center for the Blind is also located along the corridor, and the same document mentions that W. Bowles Avenue, W. Oxford Avenue, and W. Mineral Avenue are utilized by pedestrians with visual impairments. These intersections may be strong candidates for deployment of pedestrian detection systems due to the increased potential to improve safety for vulnerable users.

Consideration should be given to whether the detection will serve only as a warning to motorists, if it will automatically place calls at signalized intersections, and if it will provide extra clearance for pedestrians using a crosswalk. It should be noted that using pedestrian detection to extend green times increases delay for certain movements. In particular, pedestrian movements across Santa Fe Drive could slow down traffic and potentially interfere with timing/coordination. However, using enhanced pedestrian detection to provide motorists with warnings of pedestrians present in crosswalks may be an alternative solution to timing adjustments in this area.

Compatibility with Other ITS Technologies

+ - VMS deployed prior to intersections could be used to provide alerts to motorists based on pedestrian detection. As mentioned above, enhanced pedestrian detection could have impacts on signal timing, and therefore may conflict with other technology solutions such as adaptive signal systems and VSL systems.

Costs

$$ - Costs for enhanced pedestrian detection include camera/sensors, any warning signs, software, and cloud service would make up the bulk of the expenses for these at each location it is implemented. AI camera cost is estimated at around $7,000, and overall costs for implementing automated detectors can range from $10,000 to $70,000 per intersection [39].

Enhanced Pavement Markings

Overview

Pavement markings provide motorists with information that help them navigate a transportation network. Pavement markings can come in a wide variety of colors, widths, and material types that serve specific purposes and convey specific meanings. These markings can show drivers where they and others are allowed to drive, when they can change lanes, changes in horizontal curvature they need to navigate, edge of roadways, and when lanes are merging. Ever changing strategies and materials are constantly being evaluated for improvements to increase safety and visibility. Pavement markings, and improvements to pavement markings, therefore play a vital role in the transportation system and are an important factor in improving and maintaining a safe and efficient corridor.

Current Practices and Benefits of Enhanced Pavement Markings

Guidance and standards for pavement markings are provided in the MUTCD and supplemented by individual state Department of Transportation agency documents. MUTCD topics covered include standardization of marking meanings, retroreflectivity (low light visibility), materials used, and acceptable colors used and their meanings.

Width and retroreflectivity of pavement markings are considered two of the most important efficiency factors. Standard marking widths are 4-6 inches, and compiled research on the topic of marking widths beyond 6 inches are inconclusive and don't show any concrete evidence of operating speed or lateral displacement effects [40]. Additionally, there does not appear to be a significant improvement to safety on multilane divided highways, though there is evidence of improvements for safety on rural roads [40] [41]. However, increased marking width may have impacts on curve detection in young and old drivers in dry nighttime conditions [40]. In all, it appears that further analysis of increased marking width would be required to prove the safety and operational benefits of this enhanced pavement marking strategy.

Retroreflectivity of pavement markings affects how visible the markings are and from how far they can be detected. Retroreflectivity is particularly important in low light conditions (nighttime) and wet conditions when pavement markings are particularly difficult to see. Research has shown that retroreflectivity levels has impacts on safety benefits in both dry and wet nighttime conditions [40] [42]. Using enhanced pavement markings with higher retroreflectivity ratings and materials with different refractive properties could provide better marking visibility. Determining the appropriate material is important since specific materials are typically optimized for a single condition [43]. Additionally, pavement markings tend to lose their retroreflectivity over time as they become worn, making striping maintenance another factor to consider. As of the revised 2009 edition of the MUTCD, there are currently no standards for retroreflectivity levels, though there are a variety of ASTM methods available for evaluating retroreflectivity under specific conditions. A proposed revision to the MUTCD to include retroreflectivity requirements was put forth, but doesn't appeared to have been officially entered. In these, a minimum of 100 $mcd/m^2/lux$ would be required on roadways with speeds of 55mph or more.

There has also been some interest in pavement markings for purposes of autonomous vehicles. Standardizing width, retroreflectivity, and other striping design could allow for a smoother transition to technologies that use roadway markings for guidance [44]. Pavement marking detection already exists in some vehicles to warn drivers when they are crossing over roadway striping. Ensuring specific aspects of pavement markings are met regardless of local regulations would help facilitate future nationwide rollouts of vehicles that are able to respond to striping.

Agencies continue to adopt guidelines that promote maintaining specific retroreflectivity in markings, using specific materials to provide better visibility in night and wet conditions, and using wider striping despite some inconclusiveness in past research. This is likely due to more recently determined benefits (and some continued perceived benefits) including:

- Improved safety in dry and wet nighttime conditions
- Improved visibility of pavement markings
- Clearer guidance for motorists

Enhanced Pavement Markings and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

+++ - Based on the *Colorado Department of Transportation Pavement Marking Practices Guide, MUTCD,* and other standards followed by CDOT, there already exist guidelines for pavement markings. Retroreflectivity is already a requirement to ensure nighttime visibility, though minimum retroreflectivity readings are still being determined. Since this will become a standard, it will likely be applied to Santa Fe Drive. This will provide improvements by ensuring nighttime visibility remains adequate. MUTCD, used by CDOT, also requires lines to be 4 to 6 inches wide which meets the limits for which benefits were seen in research based on width. Additionally, longitudinal black markings are already used to provide contrast with the concrete pavement. It is possible to evaluate and update markings using wet-reflective striping. However, the added value may not be particularly impressive considering the limited amount of precipitation the area receives.

Compatibility with Other ITS Technologies

++ - While enhanced pavement markings would not necessarily be a strategy that synergizes with other ITS technologies in a technical sense, it can be used to enhance safety and overall guidance of drivers along the corridor. It also does not hinder any other technologies, making its application mostly independent of other factors.

Costs

$ - Compared to other roadway improvements, applying pavement markings can be relatively inexpensive. Monitoring conditions of the markings and retroreflectivity of the material regularly could add cost. Costs for wet reflective markings laid at a 6 inch width can cost more than $3,500 per mile [45].

Corridor Signal Timing and System Improvements

Overview

Intersection operations and the general movement of traffic through a corridor is heavily dependent on traffic signal timing. There are a wide variety of strategies and equipment that can be used to improve and maintain corridor operations.

Current Practices and Benefits of Corridor Signal Timings and Systems Improvements

Traffic signal timing is a core concept of traffic engineering. Optimizing signal timing involves detailed analysis of existing traffic conditions to determine how changes in phasing, green time, yellow time, and pedestrian times might impact delay experienced by motorists using an intersection. Maintaining and updating signal timing is important throughout a traffic signals lifetime and ensures that impacts of changing corridor conditions will be minimized, and motorists will experience acceptable, or at least less, delay in comparison to no action being taken. While single intersections can be optimized for localized conditions, signals along a corridor can be optimized and coordinated to facilitate continuous progression of vehicles. This is typically done by evaluating vehicle departure from one signal and arrival at the next based on vehicle speeds and phasing. Engineers attempt to time downstream signals to present a green phase when drivers arrive, allowing for uninterrupted flow. This strategy is optimal for corridors which motorists will travel through a large portion and has closely spaced intersections. Other signal timing and system improvements include automated traffic signal performance measures and adaptive traffic signal control, which are discussed in more detail in the following sections.

In addition to signal timing, equipment plays a crucial role in efficient traffic operations. Traffic signal controllers (TSCs) are the “brains” inside the cabinet that control traffic signal phasing and timing. They can also be programmed to operate other dynamic systems such as ramp meters and reversible lanes. GPS clocks in controllers play a crucial role in ensuring time of day plans will be executed at intended hours and that coordinated signals are operating on the same clock to allow for proper progression along the corridor. Routine checks can also ensure there are no detector issues such as malfunctioning loop detectors, video detection, or pedestrian push buttons.

There are a range of controller types in common usage today, with their native capabilities largely determined by the standard upon which they are built. In order of lesser to greater capabilities, these standards include NEMA TS-1, NEMA TS-2, Type 170, and Advanced Transportation Controller (ATC). Firmware updates can be installed on each to enhance capabilities and enable new functionality. Because the software platform for the older controllers is typically proprietary, firmware updates that can be installed are often limited – making custom applications more difficult to implement. Conversely, the ATC standard is based upon an open architecture hardware and software platform that can support custom applications for an essentially unlimited range of ITS capabilities. Even if legacy controllers receive appropriate firmware upgrades, their functionality may still be restricted by the capabilities of their native on-board processor and communication bus. For these reasons, ATC controllers are much more versatile in terms of implementing advanced capabilities and are thus preferred for use with connected and autonomous vehicle applications.

Another important element of traffic signal controllers that enables advanced functionality is the ability to transmit SPaT and MAP messages. These messages allow connected vehicles to identify the status of a traffic signal and time remaining until the signal changes, and intersection geometry data, respectively. Given the safety-critical nature of applications associated with SPaT, it is important that controllers be capable of sending and receiving this data at a high frequency. Many newer traffic signal controllers are capable of outputting signal status 10 times per second. It must be noted that the standards that govern signal controller interfaces for SPaT data are still being developed and are subject to change. As a result, controllers that currently support SPaT may still need to be upgraded as newer standards are developed to allow interoperability with newer devices and vehicles. For this reason, additional cabinet space may be needed to accommodate additional hardware to enable SPaT related functionality.

Benefits of updating signal timing and equipment include:

- Reduced delay
- Overall improved operations and corridor progression

Corridor Signal Timing and System Improvements and Santa Fe Drive: Costs, Upgrades, Updates

Ease of Implementation

+++ - Maintaining and upgrading signals and controllers along the corridor, where needed, could be highly beneficial to prevent traffic issues related to detection and controller GPS clock issues. Retiming traffic signals would be a good strategy at signals that have not been serviced in approximately three to five years to ensure they are set for current conditions. Coordination of signals may be difficult due to the distance between existing signals. The further signals are from each other, the more time platoons of vehicles have to spread out, making it difficult to ensure the platoon arrives as a group during the green phase. However signalized urban arterials are typically coordinated, and doing so where signals are close together would still likely see benefits.

Compatibility with Other ITS Technologies

+++ - Updating controllers would offer extra compatibility with other ITS technologies, and may even be required for some such as Adaptive Traffic Signal Control (discussed below) and for Automated Traffic Signal Performance Measure (discussed below) data collection. Table 2 shows some of the controller types present on Santa Fe Drive and their potential for advanced capabilities.

Table 2. Santa Fe Drive Controller Types

Controller Type	TSC Standard	Advanced Capability Readiness
Intelight	ATC	High
Econolite ASC/3	Type 170	Mid
Econolite ASC/2	NEMA TS-2	Low

Cost

$ - Retiming and optimizing signal timings would not be particularly expensive, especially when compared to other ITS technologies, coming in at around $3,500 per intersection [46]. Traffic signal controllers and cabinets are not particularly expensive with estimated costs being more than $20,000 per intersection, and would only be necessary if there were issues with detection and GPS times [47].

Automated Traffic Signal Performance Measures

Overview

Automated traffic signal performance measures (ATSPM) are sets of traffic and signal data collected that are processed at high resolution to analyze and pinpoint traffic signal issues and performance. Data of interest in ATSPM is typically related to phasing issues caused by faulty detectors, but can also include congestion and delay issues collected by installed sensors. ATSPM is used to maintain traffic signal integrity and function by addressing errors revealed by collected data.

Current Practices and Benefits of Enhanced Pedestrian Detection

There are a wide variety of performance measures and software that have been developed by several institutions, agencies, and private entities that are used in ATSPM. The data is typically collected in the field and stored in controllers and transferred to servers via a communication network [48]. Some of the most prevalent of these performance measures include metrics developed from research conducted by Purdue University and Indiana DOT beginning in 2002 [49]. Common performance measures have since grown. Table 3 shows common performance measures and the type of detection required to collect the data.

Table 3. Common Performance Measures and Detection Types [49]

Detection Type Required	Common Performance Measure
High-resolution Controller Only (no additional detection needed)	Purdue Phase Termination
	Split Monitor
	Pedestrian Actuation / Delay
	Preempt Duration
Advanced Count Detection (400 feet behind stop bar)	Purdue Coordination Diagram
	Approach Volume
	Volume-to-Capacity Ratio
	Purdue Link Pivot
	Platoon Ratio
	Arrivals on Red
	Approach Delay
	Executive Summary Reports
Advanced Detection with Speed	Approach Speed
Lane-by-lane Count Detection	Turning Movement Counts
	Red / Yellow Actuation
Lane-by-lane Presence Detection	Split Failure
Probe Travel Time Data	Purdue Travel Time Diagram

As can be seen, many of these performance measures are related directly to common intersection signal operations such as phase termination, pedestrian actuation, preemption, coordination, red / yellow actuation, and split failure. Collection, processing, and evaluation of this data would typically require field visits by technicians or engineers who would subsequently monitor conditions. Utilizing ATSPM allows for remote daily monitoring of issues that result from failures of these operations. It also allows monitoring performance of newly installed traffic signal timings. Thresholds for certain measures can be set to allow for automatic detection of issues. An example of a commonly utilized performance measure is the Purdue Phase Termination Diagram, which graphically shows traffic trigger events such as max-out, force-off, and gap-outs [50]. This can be used to show anomalies such as max-out calls during times of the day when traffic would be expected to be relatively low such as late night and early morning hours [50].

Installation of ATSPM tools is not particularly equipment intensive and can be utilized with detection devices, high resolution controllers, communications (fiber optics, cellular modem, etc.), and data storage [49]. Controller types compatible with ATSPM can include high resolution Econolite, Peek, Siemens, Intelight, Trafficware, and McCain controllers [49]. Several states already utilize ATSPM and have made it an integral part of their transportation activities. For example, Utah Department of Transportation (UDOT) makes use of its own data collection suite to monitor its traffic signals and is collecting data from nearly 99% of its 1,271 traffic signals [50]. Other agencies within Utah have connected about 90% of their signals to the same suite allowing for larger impact of signal monitoring which has resulted in a reduction in public complaints and requests for traffic signal retiming [50]. Georgia Department of Transportation has implemented ATSPM using the same management software that UDOT developed [50]. They use the software to monitor and manage operations and develop alternate routes. They have 6,775 signals currently operating under their ATSPM, which constitutes 59% of signals they monitor.

It should be noted that ATSPM tools are not a means of automatically fixing issues. Rather it is a passive means to inform professionals of deficiencies. Regardless, agencies that have applied this tool have reaped benefits which include [49]:

- Remote monitoring
- Travel time savings and delay reductions
- Safety improvements
- Maintenance cost improvements of traffic signals

Automated Traffic Signal Performance Measures and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

++++ - ATSPM tools would be a good addition to a corridor that often experiences congestion and unplanned incidents such as Santa Fe Drive. Ensuring traffic signals are operating as intended based on optimized timings and detection will help ensure that congestion is not compounded by both events and malfunctioning traffic signals. As mentioned earlier, requirements for ATSPM are minimal compared to many other technologies discussed in this paper and are less infrastructure intensive. The main components to ensure are compatible with a central system software for ATSPM would be detectors and compatible controllers. Good starting locations for ATSPM would be high congestion intersections to ensure detection and operations at these locations are operating correctly. These might include Bowles Avenue, Belleview Avenue, and intersections north of Dartmouth Avenue; however additional communications infrastructure would need to be installed for the northern intersections.

Compatibility with Other ITS Technologies

++++ - ATSPM would not interfere with any other ITS technologies and could utilize much of the existing infrastructure such as video detection and the fiber optic network. Monitoring signal performance would likely only add benefits to the corridor. Constant issues on the corridor could be verified to not be (or be) related to signal and detection issues and shift focus to decreasing delay caused by congestion or incidents, which other technologies are used to mitigate.

Cost

$ - Costs for implementing ATSPM are low. Maintenance for signals utilizing ATSPM are around $3,500 per signal, while implementation costs for up to 50 signals can be as low as $20,000 [48], depending on the equipment and infrastructure present at each intersection. New video detection may also be required to enable some aspects of ATSPM at intersections that are not currently equipped.

Adaptive Traffic Signal Control

Overview

Adaptive traffic signal control (ATSC) systems use data collected from field sensors to evaluate traffic conditions in real-time and adjust traffic signal timing accordingly to optimize traffic flow. This can occur at a single intersection or be coordinated between multiple traffic signals in a cluster or along a corridor. ATSC is typically installed with a target aspect for optimization at traffic signals including throughput, reducing delay, and equal distribution of green time [51].

Current Practices and Benefits of Adaptive Signal Control

ATSC is a technology solution that has been in use for decades but has been met with varying success. This may be due to the specific circumstances in which ATSC operates most effectively. ATSC is best suited for corridors with high variability and unpredictable traffic demand [51]. Appropriate implementation is crucial and may not be suitable for oversaturated conditions [51]. When applied appropriately, it can result in significant improvements in travel time reliability [52]. Studies suggest that on average, ATSC improves travel times by 10%, with up to 50% improvements seen on some corridors [53].

ATSC systems are available from a variety of vendors, with some limited to small scale deployments of ten to twenty intersections, and others capable of large-scale deployments across hundreds of signals. Systems have been developed over the years by private and public sector entities which typically fall into two categories, central systems and distributed systems [51]. Central systems process and distribute signal timings via a central processor, while distributed systems process timings at each controller and communicate directly with other controllers or processors [51]. Specific systems include Split Cycle Offset Optimization Technique (SCOOT), Adaptive Control System (ACS) Lite, Sidney Coordinated Adaptive Traffic System (SCATS), and Real-Time Hierarchical Optimized Distributed and Effective System (RHODES) among others [51]. Systems may rely on varying logical frameworks to determine when and how to adapt signal timing, with some vendors utilizing proprietary algorithms. Preferred or optimized timings can be used as the base around which updated traffic signal timings are modeled on, and historic data or these preferred signal timings can be used in cases of detector malfunction [54]. More complex systems operate by loading real-time conditions into traffic simulation models, and performing multiple simulations with different signal timing configurations to determine which sequence is most effective [55]. Different systems may also require different types of sensors and placement, and may have varying levels of interoperability with existing equipment. For example, some systems may be compatible with existing controllers, while other systems may require installation of new equipment and consideration for future ITS planning. Sensors used in ATSC data collection can include video and IT based cameras and microwave vehicle presence sensors for vehicular volumes and speeds [54].

Examples of adaptive signal technology in Colorado include a multi-jurisdictional adaptive signal system among Centennial, Lone Tree, and Greenwood Village which includes dozens of intersections along

Yosemite Street utilizing new sensor and camera technology [56]. This multi-jurisdictional collaboration, set up in 2020, serves as a reminder of the challenges and considerations that go into setting up ATSC along a corridor the spans townships and counties. Other examples include installation of ASCT in Greeley and Woodland Park in 2011 [54]. Considerations for using this technology for these projects included heavy and irregular demands, high side street traffic, and high weekend traffic from recreational access. MOEs were evaluated to determine improvements along the corridor which included travel time, fuel consumption, LOS, average number of stops, physical surveys, and benefit cost. Results from this evaluation showed improvements to travel time, fuel consumption, cost savings, and fewer stops. There were mixed delay results and LOS ranging from significant degradation to significant improvements [54].

Benefits of adaptive traffic signal control includes [53]:

- Adaptability of signal timing network along an entire corridor
- Distribution of timing to movements that need it, including side street movements
- Improved progression through a corridor and travel time reliability
- Reduction of congestion

Adaptive Traffic Signal Control Systems and Santa Fe Drive: Cost, Upgrades, Updates

Ease of Implementation

++ - Assuming signalized intersections remain in the final corridor configuration, the unpredictability of traffic demand on Santa Fe Drive suggests it would be a prime candidate for ATSC. Furthermore, Santa Fe is an incident management plan (IMP) corridor for southbound I-25, meaning that ATSC could be particularly beneficial in the event of incidents on the interstate where traffic is diverted to Santa Fe Drive. However, implementation would likely require significant equipment upgrades and coordination between agencies. Sensors must be placed at every intersection to measure traffic conditions in each lane of traffic on the mainline, and potentially on crossroads. While the advanced data collection capabilities of Littleton's CCTV cameras at Bowles, Prince, and Mineral could potentially be used for ATSC applications, the majority of intersections would require deployment of additional sensors. Currently there are ATC traffic signal controllers on the corridor, however some controllers would likely need to be replaced to enable ATSC implementation.

Along the study corridor, traffic signals are maintained by CDOT, CCD, and Littleton, with communications from the signals backhauled to these respective agencies. Corridor-wide implementation of ATSC would require agreements and permissions to be established between the agencies to allow signal operations to be controlled from a central location. Upgraded IT infrastructure and cyber security measures may also be necessary. Extending the fiber optic backbone north of Dartmouth would likely be required to ensure all signals on the corridor will be able to communicate new and changing timings between each other. The framework for such coordination has already been established, as a pilot agreement between the agencies (as well as the City of Englewood) was implemented through DRCOG during the Santa Fe IMP project. If coordination along the entire corridor is infeasible in the short term, an interim solution could involve ATSC being installed in "clusters" managed by the agencies that maintain the signals. The benefits of the system could then be further evaluated to determine whether additional coordination between signals and agencies is warranted.

Compatibility with Other ITS Technologies

+++ - ATSC would likely be highly compatible with a wide variety of ITS technologies including video detection, MVRD, and existing fiber optics. It may also synergize well with other technologies discussed in this paper such as VMS and queue warning systems which provide drivers knowledge of corridor issues while ATSC works in the background to facilitate unpredictable traffic demand. However, impacts that active transportation management have on ATSC should be considered as the effects of these combinations would be unknown. For example, VSL would impact travel speeds which is used as an input in many ATSC systems. Determining the objectives of implementing ATSC would need to be balanced with expected impacts other ATM technologies would have on Santa Fe Drive.

Cost

$$$ - Costs associated with implementing ATSC include hardware and sensors, trained technicians to maintain the system, software, and the engineering needed to design the timing. ASCT is not necessarily a plug and go system; trained and knowledgeable personnel are important for continued efficiency for the system. Costs can vary widely by intersection, averaging $45,000 per intersection and ranging from $10,000 to $120,000 per intersection [51]. Examples in Colorado have cost ranges between $100,000 to nearly $1 million depending on the technology installed chosen, number of intersections, and existing infrastructure [54].

Summary

Santa Fe Drive is a unique corridor that combines elements typical of freeway travel, such as HOV lanes and an extensive ITS network, with a signalized arterial. High traffic volumes and frequent congestion open the corridor to a wide variety of potential solutions to help mitigate these issues. This paper has pulled together information about several ITS technologies being considered for Santa Fe Drive. Each section has listed background information, summarized current state of practice, and discussed different aspects of how the ITS technology may be beneficial for Santa Fe Drive. Each technology has advantages and disadvantages, cover a wide range of costs, and has varying degrees of difficulty to implement based on existing infrastructure. Table 4 presents the information most relevant to Santa Fe Drive in a condensed summarized version. The most immediate and impactful ITS solutions for Santa Fe Drive include expanding the communications infrastructure along the entire corridor, enhanced TOC capabilities and CCTV coverage along the corridor where blind spots may exist, implementing traffic signal performance measures to ensure signals operate in a manner efficient for the corridor, and ensuring signal optimization and equipment is up to date. From here, consideration of future planning on Santa Fe Drive will help direct choices for other technologies such as VMS and queue warning systems to warn motorists of incidents on the corridor, and ensuring incident response protocol is adequate for the corridor.

Table 4. Summary of ITS Technology Factors

Technology Element	Ease of Implementation	Compatibility	Cost	Potential Locations	Benefits
Traffic Operations Center	++++	++++	$	N/A	- Active monitoring of corridor conditions - Deployment of incident response in real-time - Ability to actively send alerts to motorists - Improve travel times and speeds
Enhanced Communications Structure	++++	++++	$$$$	Between I25 and Dartmouth	- High bandwidth, reliable connections to ITS devices, and redundant communications to traffic signals and other equipment - Important enabler of other ITS technologies
Incident Management Plan	+	+++	$$	N/A	- Reduction in delay due to traffic incidents - Avoids rerouting and unplanned detours - Economic savings from reduced delay and improved safety for drivers - Improved safety of incident responders - Reduction of secondary crashes
Improved Traveler Information Signs	++++	++++	$$	South of Mineral Ave, North of Mississippi Ave	- Ability to convey information to every motorist passing the sign location - Increased driver situational awareness - Displays supplemental information for VSL and queue warning systems
Queue Warning Systems	+++	+++	$$$	Dartmouth, Oxford, and Mineral Avenue	- Reduce rear end crashes and secondary crashes - Warning motorists of queues and reduced speeds - Speed harmonization - Improved travel times
Variable Speed Limit System	+++	++	$$$	Dartmouth, Oxford, and Mineral Avenue	- Potential for reduced crash rates - Potential for reduced crash severity - Potential for shorter travel times - Improved travel time reliability - Ability to reduce vehicle speeds in inclement weather
Wayfinding Apps	+++	+++	$	N/A	- Provide reliable step by step directions - Provides travel time and travel information - Provides alternate routes to avoid congestion and traffic - Collaboration of both crowdsourced data and transportation agency data
Enhanced Pedestrian Detection	++	+	$$	Mississippi, Iowa, Evans, Bowles, Oxford, and Mineral Ave	- Increased pedestrian safety - Reduction of pedestrians that cross during don't walk symbols - Reduction in pedestrian/vehicle conflicts

Technology Element	Ease of Implementation	Compatibility	Cost	Potential Locations	Benefits
Enhanced Pavement Markings	+++	++	$	Entire corridor	- Improved safety in dry and wet nighttime conditions - Improved visibility of pavement markings Clearer guidance for motorists
Corridor Signal Timing and System Improvements	+++	+++	$	Signals with old timing or equipment	- Reduced delay - Overall improved operations and corridor progression
Automated Traffic Performance Measures	++++	++++	$	Bowles, Belleview, and Mineral Avenue. North of Dartmouth Avenue	- Remote monitoring - Travel time savings and delay reductions - Safety improvements - Maintenance cost improvements of traffic signals
Adaptive Traffic Signal Control	++	+++	$$$	Bowles, Belleview, and Mineral Avenue for southern portion. Intersections north of Dartmouth.	- Adaptability of signal timing network along an entire corridor - Distribution of timing to movements that need it, including side street movements - Improved progression through a corridor and travel time reliability - Reduction of congestion

Ease of Implementation
+ - Has most barriers to pass before implementation.
++++ - Has least barriers to pass before implementation.

Compatibility
+ - May interfere with other technologies.
++++ - Synergizes well and supports goals and objectives of other technologies.

Cost
$ <$250,000
$$ $250,000 - $500,000
$$$ $500,000 - $750,000
$$$$ >$750,000

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