White Paper

Improving the Cost-Effectiveness of Urban Freeways

Through Flexibility in Operations and Design

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Executive Summary

The level of future uncertainty in transportation planning, and more specifically in addressing prevailing congestion on urban freeways, has increased significantly over the past few years. The impact of connected and autonomous vehicles on traffic flow, of Mobility as a Service (MaaS) initiatives, particularly the car-sharing elements, and exciting advances in traffic operations are some of the factors contributing to this uncertainty. The FHWA recently acknowledged uncertainty in its recent publication "Advancing Transportation Systems Management and Operations through Scenario Planning."

Thus, investment of billions of dollars in projects to widen congested urban freeways has become risky and might be a misappropriation of scarce transportation funds. This white paper provides solutions to future uncertainty when addressing congestion. Specifically, it explains how flexibility can be incorporated in urban freeways to cope with unexpected developments and alternative futures while also addressing prevailing traffic congestion at low cost.

As part of this white paper, two options were considered: a comparison was made between widening a congested urban freeway by constructing one additional lane in each direction, or providing a reversible lane using movable barrier to create an additional lane during the peak period in the peak direction for both the a.m. peak and the p.m. peak. Here are the main findings:

- Cost for constructing a lane mile to widen an urban freeway averages $28 million. In contrast, the cost to provide a reversible contraflow lane is $1.4 million per mile.
- The typical length of time to plan, design and construct an additional lane is 10 years. Equivalent time for a reversible lane is 1-4 years.
- The environmental impact associated with construction of an additional lane is significant and requires an environmental impact statement which typically takes 3 years to complete. The impact of a reversible lane is minor and does not require an environmental impact statement. In most cases it qualifies for a categorical exclusion.
- Once funds are spent on construction of additional freeway lanes it is not possible to recoup or change this significant investment. The high cost of this alternative, therefor is potentially a high risk, considering the uncertainty of the future. Reversible lanes using movable barrier are flexible by contrast in terms of coping with existing and future innovations by changing the number of contraflow lanes; when contraflow lanes are implemented; and even where they are applied. Because of the relatively low cost of this alternative, the associated risk is also low.

The white paper also provides information about the impact of an additional lane on a congested urban freeway in terms of growth of traffic in the years following the widening. From available literature it was determined that "new vehicles" attracted to a freeway (induced traffic, and excluding diverted traffic) will typically result in the freeway experiencing the same level of congestion as prior to the added lanes within ten years or less from the opening the new lanes. The same applies when the additional lanes are provided in the form of reversible lanes using movable barrier. However, the critical factor is the order of magnitude difference in capital funds invested in providing the additional capacity. This variance in capital expenditure is highlighted in a benefit-cost analysis included in the white paper and summarized in the paragraph below.

A straightforward addition of a lane in each direction of a congested freeway over ten miles was assumed for the benefit-cost analysis. Results show that when the additional lanes were provided through construction the benefit-cost ratio was only 0.24. When reversible lanes using movable barrier were added, the benefit-cost ratio was found to be 3.4. That the benefit-cost ratio for reversible lanes is higher than that for adding lanes by construction is intuitively what can be expected. However, what is significant is that the option to add the lanes through construction does not get close to 1.0. This indicates that if the sole purpose of constructing additional lanes on a congested urban freeway is to relieve congestion, then there is a probability that it will not be a viable project in terms of the return on the investment.
To obtain a benefit-cost ratio of more than 1.0, the additional lanes needs to be constructed at less than $4 million per lane mile.

As shown in the table below, a directionality split of as low as 43%/57% can be good enough for a reversible lane on an eight-lane freeway. If a limited amount of congestion can be tolerated in the off-peak direction, considering that overall there will be significantly less delay on the freeway, the directional split can be lower than the percentages in the table.

Table 12. Minimum Directional Split Requirement for Contraflow Lane Application on a Freeway

Number of Lanes (total,both directions)	Percentage Traffic in Off-Peak Direction	Percentage Traffic in Peak Direction
4	33	67
6	40	60
8	43	57
10	44	56

This paper also illustrates several ways reversible lanes using movable barrier can be applied and is summarized in the table below.

Options for Applying Reversible Managed Lane Systems Using Movable Barrier			
Contraflow	Movable Median	Contraflow Within a Two HOT Lane per Direction System	Contraflow HOT Lanes Using Existing HOV Lanes
Option 1 Provide one or two additional lane(s) depending on directional split, in a.m. peak period direction. Option 2 Provide one or two additional lane(s) depending on directional split, in p.m. peak period direction.	Option 1 Provide one or two additional lane(s) depending on directional split, in a.m. peak period direction. Option 2 Provide one or two additional lane(s) depending on directional split, in p.m. peak period direction.	Option 1 Provide one additional HOT lane in a.m. peak period direction for a total of three HOT lanes in a.m. peak direction. Option 2 Provide one additional HOT lane in p.m. peak period direction for a total of three HOT lanes in p.m. peak direction.	Option 1 Provide one additional lane in a.m. peak period direction for a total of two HOT lanes in a.m. peak direction. Option 2 Provide one additional lane in p.m. peak period direction for a total of two HOT lanes in p.m. peak direction.

Note:
The reversible managed lanes are ideal facilities for accommodating express buses and autonomous vehicles.

On September 23, 2016, the California state legislature passed Bill AB 2542 that requires that, prior to the California Transportation Commission (CTC) approving a capacity-increasing project or major street or highway lane realignment project, the California Department of Transportation (Caltrans) or a regional transportation planning agency must demonstrate that reversible lanes were considered for the project. This legislation recognizes the cost-effectiveness of reversible lanes.

In summary, this white paper provides solutions to future uncertainty when addressing congestion. More specifically it explains how flexibility can be incorporated in urban freeways at low cost to be able to cope with unexpected developments and alternative futures, while also addressing prevailing traffic congestion and accommodating express bus services, autonomous vehicles, and carpool vehicles.

1. Purpose of this White Paper

The following factors have changed the outlook for addressing congestion on urban freeways:

- The extremely high cost to physically add capacity in built-up locations particularly where there is not sufficient right-of-way available.
- Advances in urban freeway operations such as Reversible Lanes, Integrated Corridor Management (ICM) including Active Traffic Management (ATM) and Corridor and Arterial Traffic Management as well as Travel Demand Management.
- Recent successful Mobility as a Service (MaaS) initiatives, particularly the car-sharing components.
- Connected vehicles and autonomous vehicles.

The last two items above have introduced a measure of uncertainty in the planning of urban freeways particularly since they have only come about recently, begging the questions, what next? The FHWA recognized the need to look at alternative futures in its recent publication "Advancing Transportation Systems Management and Operations through Scenario Planning" (https://ops.fhwa.dot.gov/publications/fhwahop16016/fhwahop16016.pdf). The message is clear that the future is not as predictable as it has been in the past. If this uncertainty is not recognized and addressed as part of the planning of urban freeway corridors there is a real likelihood that mistakes might bel be made. These mistakes are typically recommendations for significant capital investment to reduce congestion by constructing additional traffic lanes when an alternative approach might be at least as effective in reducing congestion at a fraction of the cost.

This white paper provides solutions to future uncertainty when addressing congestion. It explains how flexibility can be incorporated in urban freeways at low cost to cope with unexpected developments and alternative futures, while also addressing prevailing traffic congestion.

2. Reducing Congestion and Increasing Safety of an Urban Freeway: A Comparison of Two Alternatives

There are two main alternatives for reducing congestion and increasing safety on congested urban freeways. The first approach is the conventional practice which is to add freeway lanes through construction. The second approach is to rely on improved traffic operations including reversible lanes. Each of these two approaches will be described in terms of critical factors and then compared.

2.1 Alternative A – Constructing Additional Freeway Lanes

It is common practice to reduce congestion on urban freeways by constructing additional lanes. The following are key characteristics of such an approach:

2.1.1 Key Characteristic 1: Typical Cost to Add Lanes

See Table 1 below.

Table 1. Typical Costs per Lane Mile of Freeway for Adding a Lane (TOTAL COST)
(Cost Includes Bridges, Interchanges, and Right-of-Way)

Type of Urban Area	Add Lane, Normal Cost (2017 $s, millions)	Add Lane, High Cost (2017 $s, millions)
Large Urban Area (population between 200,000 and 1,000,000)	$5.4	$18.1
Major Urban Area (population of more than 1 million)	$10.8	$44.9

Source:
2015 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance, USDOT
Note:
"Normal Cost" reflect costs of projects for which sufficient right-of-way is available or readily obtained to accommodate additional lanes.
"High Cost" are intended to reflect situations in which right-of-way is extremely expensive and conventional widening is infeasible and alternative approaches are required to add capacity to a given corridor.

2.1.2 Key Characteristic 2: Length of Time to Implement Additional Lanes

U.S. Government Accountability Office study:
According to a report by the U.S. Government Accountability Office (GAO), it typically takes between 9 and 19 years to complete the planning, gain approval of, and construct a new major

federally-funded highway project (Opportunities for Oversight and Improved Use of Taxpayer Funds, United States General Accounting Office).
In addition, the project might take longer when funding is uncertain, considering the high cost of expanding an urban freeway, as provided in Table 1.

Illinois Department of Transportation Experience:
A further source addressing the time it takes for a major construction project to be completed is provided by the Illinois Department of Transportation: "The funded highway project process can involve as many as 55 steps and take many years to finish. A major construction project involving a new highway, for instance, can take from five to 20 years to complete all the steps." (It Takes Time – Highway Construction From Start to Finish).

Virginia Department of Transportation Experience:
The Virginia Department of Transportation provides the following information on the time it takes for each of the major steps to be completed for highway project:

1. Planning Phase may last from 1-24 months.

2. Scoping Phase may last between 1-8 months depending on project complexity.

3. Preliminary Design Phase may range from 1-18 months.

4. Detailed Design Phase may last between 1-12 months.

5. Final Design and Right of Way Acquisition Phase may range from 1-24 months.

6. Advertisement Phase may last from 1-5 months.

7. Construction Phase may range from 1 to over 36 months.

The total time ranges from less than a year to 10 years.

Table 2 below provides a summary of the three sources of information.

Table 2. Typical Length of Time to Construct Additional Lanes to an Existing Urban Freeway	
Source	Number of Years for Planning, Design, Approval and Construction of Lane Additions to an Existing Freeway)
U.S. Government Accountability Office	9 to 19
Illinois Department of Transportation	5 to 20
Virginia Department of Transportation Experience	1 to 10
Average	**10 years**

2.1.3 Key Characteristic 3: Length of Time Before Same Level of Congestion is Reached After Constructing Additional Lanes

After lanes are added to an existing urban freeway, the additional capacity reduces peak period congestion and speeds increase. The reduced level of congestion on the freeway is attractive to motorists that might have travelled other routes, other times, or may not even have made a trip at all due to congestion. The result is a higher level of growth in peak period traffic, and particularly peak hour traffic. This higher level of growth continues until congestion again limits further peak-period traffic growth.

The general term used for the additional traffic is “generated traffic.” Generated traffic consists of diverted traffic and induced traffic.

Diverted Traffic

Diverted traffic consists of trips that shifted in time (e.g. a commuter finding it possible to leave home a bit later to go to work since the level of congestion has decreased at the later time), shifted in route (e.g. a commuter changing his/her route from an arterial running parallel to the freeway where lanes have been added since the travel time is lower), and shifted in destination (e.g. a person changing the location to obtain gas by using the freeway where lanes have been added since the travel time is lower).

Induced Traffic

Induced traffic consists of trips that shifted in mode (e.g. a commuter changing from using transit to a car since the reduced congestion on the freeway where lanes have been added make the trip by car quicker), shifted in distance (e.g. to a better shopping center that can be reached in the same time as a less preferred shopping center), and a new vehicle trip (e.g. conducting a meeting in person rather than by phone since the trip time is acceptable).

A Safety Benefit of Diverted Traffic

Typically, diverted traffic results in an increase in traffic on the freeway where lanes have been added but also results in a reduction in traffic on routes that run parallel or reasonably close to the freeway. Diverted traffic is often a safety benefit since the crash rate on freeways is lower than other road types, as shown in Table 3.

Table 3. Crash Rate of Freeways and Other Urban Road Types

Urban Road Type	Crashes per 100 Million Vehicle Miles Traveled
Freeway	130
Multilane divided road	440
Multilane undivided road	550
Two-Lane road	380

Source: Adapted from - HERS-ST Highway Economic Requirements System - State Version: Technical Report - Chapter 5: Estimation of Impacts, FHWA (Updated June 2017)

Induced traffic is additional travel including new trips which increases the growth of traffic at a higher rate than what would have taken place without the road widening. Table 4 provides information on studies conducted to determine induced travel as a percentage of all future travel.

Table 4. Induced Traffic as a Percentage of Additional Capacity		
Author of Study on Induced Traffic	Induced Traffic as a Percentage of Additional Capacity Within 3 Years	Induced Traffic as a Percentage of Additional Capacity in the Long Term (3+ years)
Goodwin	28%	57%
Fulton, et al	10 – 40%	50 - 80%
Noland	20 - 50%	70 – 100%
Source: Adapted "Generated Traffic: Implications for Transport Planning" by Todd Litman, Victoria Transport Policy Institute, April, 2017		

Table 4 provides information on induced traffic only. In addition to induced traffic, there is also diverted traffic and the growth of traffic that has been on a freeway where additional lanes were constructed.

Of note is a study conducted by Mark Hansen and Yuanlin Huang entitled "Road Supply and Traffic in California Urban Areas", Transportation Research A, Vol. 31, No. 3. They found that 60% to 90% of increased road capacity is filled with new traffic within five years (as cited by Todd Litman, "Generated Traffic: Implications for Transport Planning", Victoria Transport Policy Institute, April 2017).

Based on the information in Table 4 and the above paragraph, it is reasonable to assume that the same level of congestion as existed before the addition of freeway lanes will again take place within approximately 10 years of implementation of the additional lanes.

In urban areas, where congestion is common, the percentage of induced traffic due to adding lanes to a freeway tends to be higher. The amount of induced traffic provided in Table 4 is significant. Induced traffic also has an impact on the benefit-cost ratio of a freeway widening where, when taken into consideration, there is a likelihood for the ratio to be less than one and therefore not a good investment, economically.

2.1.4 Key Characteristic 4: Environmental Impact

The following are possible environmental impacts associated with widening an urban freeway:

- During construction:
    - Additional traffic congestion.
    - Possible delay to first responders.

  - Short-term degradation of air quality may occur due to the release of particulate emissions (airborne dust) generated by excavation, grading, hauling, and other activities related to construction.
  - Emissions from construction equipment also are anticipated and would include CO, NOx, VOCs, directly-emitted particulate matter (PM10 and PM2.5), and toxic air contaminants such as diesel exhaust particulate matter.
  - Noise (particularly at nighttime) and vibration.
- If additional right-of-way is required, residential and/or commercial property might have to be taken through eminent domain.
- Induced traffic will increase air pollution from fossil (and some biofuel) powered vehicles. Emissions include particulate emissions from diesel engines, NOx, volatile organic compounds, carbon monoxide and various other hazardous air pollutants including benzene. The impact is further increased if the widening of the freeway results in vehicles traveling closer to adjoining developments particularly residential development. concentrations of air pollutants and adverse respiratory health effects are greater near the road than at some distance away from the road.
- Adding additional lanes will increase impervious surfaces. Urban runoff from roads and other impervious surfaces is a major source of water pollution. Rainwater and snowmelt running off of roads tends to pick up gasoline, motor oil, heavy metals, trash and other pollutants. Road runoff is a major source of nickel, copper, zinc, cadmium, lead and polycyclic aromatic hydrocarbons (PAHs), which are created as combustion byproducts of gasoline and other fossil fuels.
- Noise pollution will increase due to the higher overall traffic volume and possibly due to vehicles being closer to adjacent developments.

2.1.5 Key Characteristic 5: Coping with Uncertainty

It is generally recognized that urban transportation is undergoing fundamental changes. Two examples are provided below.

<u>Mobility as a Service (MaaS)</u>
MaaS includes car-sharing services such as Zipcar, ride-sharing services such as Lyft or Uber, and bike-sharing. A recent study co-sponsored by the Minnesota Department of Transportation and the Minnesota Local Road Research Board entitled “The Transportation Futures Project: Planning for Technology Change” with principal investigator David Levinson, Professor, Civil, Environmental and Geo-Engineering at the University of Minnesota, addressed MaaS in terms of its impact on transportation planning. The following implications of MaaS were determined:

- “A smaller, more modern fleet that is used more efficiently and turns over faster.”
- “Greater coverage in urban areas with higher demand.”
- “Fewer trips for people who give up on vehicle ownership and opt to pay by trip.”

- “Greater viability for the electrification of the vehicle fleet.”
- “Demand for new street designs that emphasize pick-up and drop-off locations rather than on-street parking.”

Ken Buckeye, program manager with MnDOT’s Office of Financial Management said “importantly, transportation sharing is likely to encourage rational consumer behaviors that will have consequences for system performance.”

The Impact of Connected Vehicles (CV) and Autonomous Vehicles (AV) on Freeway Capacity

A study entitled “Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity” by the FP Think Working Group members Jane Bierstedt, Aaron Gooze, Chris Gray, Josh Peterman, Leon Raykin, and Jerry Walters analyzed by means of VISSIM simulation the impact of “next generation vehicles” on freeway capacity. The study concluded that “capacity benefits are likely to occur only on freeways when the fleet mix is at least 75% autonomous and assuming performance is programmed at intermediate levels between conservative and aggressive. At that point, likely post-2035, the AV fleet mix is likely to achieve traffic flow benefits of 25-35%. Beyond that, when regulations, liability concerns and driver comfort allow much more aggressive car-following algorithms, vehicle delays may be reduced by 45% or more.”

Another study conducted by Dwight Farmer, P.E., published in the ITE Journal of November 2016, concluded that fully autonomous vehicles will enable the headway vehicles to be reduced to such a degree that the maximum freeway flow rates will increase “from approximately 2,000 vehicles per hour per lane to approximately 4,000 vehicles per hour per lane.”

There is at this stage still some uncertainty on how much CV/AV will change the capacity of freeway lanes, but there seems to be increased consensus that CV/AV will increase the capacity of freeway lanes.

Considering the issues addressed above, there is presently more uncertainty in urban transportation planning. Under these circumstances, the ability for freeways to be flexible in terms of accommodating future traffic volumes is a distinct advantage. When widening an urban freeway by constructing additional lanes there is an acceptance of the existing capacity of freeway lanes (maximum vehicles per lane per hour as determined, for example, by applying the Transportation Research Board’s Highway Capacity Manual techniques) and that innovative services such as MaaS and the capacity impact of CV/AV will not significantly impact travel. This implicit assumption is highly unlikely and extremely risky considering the significant amount of capital cost at play.

2.1.6 Summary of Alternative A

Table 5. A Summary of How Alternative A (Addressing Congestion by Constructing Additional Freeway Lanes) Performs in Terms of Key Characteristics	
Key Characteristics	Performance
1. Cost to add lanes	\$11 - \$45 million per lane mile[1]
2. Length of time to implement additional lanes	Approximately 10 years[2]
3. Length of time before same level of congestion is reached after constructing additional lanes	Less than 10 years[3]
4. Environmental impact	Significant impact requiring an environmental impact statement which takes an average of 3 years to complete (included in the 10 years for key characteristic 2).
5. Coping with uncertainty	Limited and therefore a high risk.
Notes: [1]Assume freeway is located in a larger urban area. [2]Includes planning, gaining approval, and construction. [3]In some cases it can be closer to 4 or 5 years, depending on the level of congestion in the general corridor.	

2.2 Alternative B - Reversible Lanes (Contraflow)

Application of reversible lanes using movable barrier technology to create an additional lane in the peak direction is much more cost-effective than widening a freeway by constructing additional lanes. Reversible lanes have been successfully applied at 21 locations in the U.S. and elsewhere.

2.2.1 Key Characteristic 1: Typical Costs to Add Contraflow Lanes

See Table 6 below.

Table 6. Typical Costs to Add Contraflow Lanes	
Typical Cost Items for Movable Barrier Creating a Contraflow Lane in the Morning and Evening Peaks	Cost (2017 $s, millions)
Capital Costs	
Movable barrier per mile	$1,386,000
One Barrier transfer machine[1]	$1,600,000
Other costs (gates, crossovers, signage, etc.)	$3,000,000
Operating Costs	
Operating cost per year for 10 miles, both directions of freeway[2]	$840,000

Notes
[1]Usually two machines are required.
[2]As estimated by Lindsay Transportation Solutions, manufacturers of the movable barrier systems.

2.2.2 Key Characteristic 2: Length of Time to Implement Contraflow Lanes

Table 7 below provides real world examples.

Table 7. Length of Time to Implement Contraflow Lanes to an Existing Urban Freeway	
Source	Number of Years for Planning, Design, Approval and Construction of Contraflow Lanes
System can be built in less than one year. Planning and approval is dependent on the agency and is typically 1-3 years.	1 to 4 years

2.2.3 Key Characteristic 3: Length of Time Before Same Level of Congestion is Reached After Constructing Additional Lanes

Same as for Alternative A

2.2.4 Key Characteristic 4: Environmental Impact

The following are possible environmental impacts associated with implementing a contraflow lane on an urban freeway:

- During construction: no impact.
- Additional right-of-way is not required.
- Induced traffic will increase air pollution from fossil (and some biofuel) powered vehicles. Emissions include particulate emissions from diesel engines, NOx, volatile organic compounds, carbon monoxide and various other hazardous air pollutants including benzene.
- Impervious surfaces will be increased by an extremely small amount.
- Noise pollution will increase due to the higher overall traffic volume and the barrier transfer operation.

2.2.5 Key Characteristic 5: Coping with Uncertainty

Contraflow lanes are flexible in terms of addressing unexpected events. See more information about this in Section 3.

2.2.6 Summary of Alternative B

Table 8. A Summary of How Alternative B (Addressing Congestion by Implementing Contraflow Lanes) Performs in Terms of Key Characteristics

Key Characteristics	Performance
1. Cost to add lanes	Movable barrier $1,386,000 per mile. Annual operating cost[1] Fixed costs[1]
2. Length of time to implement additional lanes	1-4 years
3. Length of time before same level of congestion is reached after constructing additional lanes	Less than 10 years[2]
4. Environmental impact	Minor impact which will not require an environmental impact statement and will in most cases qualify for a categorical exclusion.
5. Coping with uncertainty	Application of reversible lanes using movable barrier is flexible in terms of coping with existing and future innovations as explained in Section 3. Because of the relatively low cost of this alternative, the associated risk is also low.

Notes: [1]Actual costs depend on specific circumstances of project.
[2]In some cases it can be closer to 4 or 5 years, depending on the level of congestion in the general corridor.

2.3 Comparison Between Two Alternatives (A and B) to Reduce Severe Congestion: Widening a Freeway by Constructing Additional Lanes or Applying Contraflow Reversible Lanes

Table 9. Comparison of Key Characteristics of Constructing Additional Lanes or Implementing Contraflow Lanes to Address Congestion on an Urban Freeway

Key Characteristics	Construction of Additional Lanes	Implementation of Contraflow Lane
1. Cost to add lanes	\$11 - \$45 million per lane mile[1]	\$1,386,000 per mile plus operating cost and fixed costs
2. Length of time to implement additional lanes	Approximately 10 years[2]	1-4 years
3. Length of time before same level of congestion is reached after constructing additional lanes	Less than 10 years[3]	Less than 10 years[3]
4. Environmental impact	Significant impact requiring an environmental impact statement which typically takes an average of 3 years to complete (included in the 10 years for key characteristic 2).	Minor impact which will not require an environmental impact statement and will in most cases qualify for a categorical exclusion.
5. Coping with uncertainty	Limited and therefore a high risk.	Application of reversible lanes using movable barrier is flexible in terms of coping with existing and future innovations as explained in Section 3 of this white paper. Because of the relatively low cost of this alternative, the associated risk is also low.

Notes:
[1]Assume freeway is located in a larger urban area.
[2]Includes planning, gaining approval, and construction.
[3]In some cases it can be closer to 4 or 5 years, depending on the level of congestion in the general corridor.

Table 10. Benefit/Cost Analysis of Widening Freeway by Constructing Lanes		
Assumptions: 1. Simplified analysis for 10 miles on six-lane urban freeway. 2. One additional lane per direction is constructed at a cost of $28 million per mile (based avg. costs in Table 9). 3. Total implementation time is 10 years. Construction starts 7 years out for three years. 4. Due to induced traffic, both alternatives experience same level of traffic congestion as before congestion after 10 years of improvements becoming operational. 5. Benefit-cost analysis is performed for 20 years starting at planning of project. 6. Congested speed is 30 mph, uncongested speed is 65 mph. Speed during construction of lanes drops from 30 mph to 25 mph. No reduction in speed is assumed with implementation of reversible lanes. 7. Vehicles per hour per lane during peak hours is 2,000 and congestion is assumed to last 2 hours. 8. Value of time is $16 per vehicle hour for commuting. 9. Discount rate = 3% per year.		
	Actual Costs and Benefits	**Present Value of Costs and Benefits**
Costs:		
Capital Costs	$560,000,000	$442,000,000
Operational and Maintenance Cost Per Year	$940,000	--
Present Value of O and M Costs (over 10 years)	--	$5,966,000
Cost of additional delay per year due to construction (over 3 years)	$6,720,000	--
Present value of additional delay due to construction	--	$15,458,000
Total Present Value Costs		**$463,424,000**
Benefits:		
Commuter time savings per year	$17,232,000	--
Present Value of commuter time savings (over 10 years, starting 10 years out in future)	--	$109,374,000
Total Present Value Benefits	**--**	**$109,374,000**
Benefit/Cost Ratio	**--**	**0.24**

To obtain a benefit / cost ratio of more than 1.0 (benefits = costs), the additional lanes needs to be constructed at less than $4.4 million per lane mile. Typically a benefit cost ratio should be in the region of at least 2.0 to be sure the project will be a good investment.

Table 11. Benefit/Cost Analysis of Reversible Lanes		
Assumptions: 1. Simplified analysis for 10 miles on six lane urban freeway. 2. One additional lane is provided in peak direction for a.m. and p.m. peaks. Costs from Table 6 are used. 3. Total implementation time for reversible lane is two years. Construction starts one year out for one year. 4. Due to induced traffic, both alternatives experience same level of traffic congestion as before congestion after 10 years of improvements becoming operational. 5. Benefit-cost analysis is performed for 20 years starting at planning of project. 6. Congested speed is 30 mph, uncongested speed is 65 mph. No reduction in speed is assumed with implementation of reversible lanes. 7. Vehicles per hour per lane during peak hours is 2,000 and congestion is assumed to last 2 hours. 8. Value of time is $16 per vehicle hour for commuting. 9. Discount rate = 3% per year.		
	Actual Costs and Benefits	**Present Value of Costs and Benefits**
Costs:		
Capital Costs (Includes movable barrier, 2 transfer machines and other fixed costs such as gates, crossovers, signage, etc.	$34,920,000	$33,904,000
Operational and Maintenance Costs Per Year	$846,446	--
Net Present Value of O and M Costs (over 10 years)	--	$6,806,000
Total Present Value Costs		**$40,710,000**
Benefits:		
Commuter time savings per year	$17,232,000	--
Present Value of commuter time savings (over 10 years)	--	$138,552,000
Total Present Value Benefits	**--**	**$138,552,000**
Benefit -Cost Ratio (over 10 years)	**--**	**3.4**

Table 10 and 11 did not include vehicle operational cost and safety costs. The amount of vehicle miles traveled is not impacted in this example and the reduction in costs due to a reduction in speed change cycles is considered low and will not have a meaningful impact on the magnitude of the benefit / cost ratio.

3. Reversible Freeway Lanes and the Associated Flexibility in Design and Operations

3.1 Overview – Why Flexibility?

In section 2.1.5 of this white paper, the possible impact of critical items such as Mobility as a Service (MaaS), particularly the ridesharing component of MaaS, and the headway reduction that will be realized by connected vehicles (CV) and autonomous vehicles (AV) addressed. There is no doubt that these initiatives will have a significant impact on future urban travel. The question is how and how much?

Tables 10 and 11 provide information to show how the approach of widening a freeway by constructing additional lanes is not cost-effective when generated traffic and, in particular, induced traffic are taken into consideration. In fact, providing additional lanes by reversing traffic flow is much more cost-effective (B/C ratio of 3.4 vs. 0.24). State DOTs have, as far as can be ascertained, often not taken into consideration the impact of induced travel. In addition, there are now many researchers who are confident that CV/AV will increase capacity. Some research indicates that AV will increase vehicle miles traveled, but nearly all research indicates that the increase in capacity is most likely higher than the increase in VMT.

All considered, if the following conditions exist:

- prevailing congestion along an urban freeway corridor, and
- a reasonable amount of directionality (see table 12 below),

then applying a reversible lane will outperform adding additional lanes by widening of the freeway.

As shown in Table 12, a directionality split of as low as 43%/57% can be good enough for a reversible lane on an eight-lane freeway. If a limited amount of congestion can be tolerated in the off-peak direction, considering that overall there will be significantly less delay on the freeway, the directional split can be lower than the percentages in Table 12.
Considering the above and the information provided in section 2, it is highly advisable to be able to maintain flexibility in terms of meeting the demands of present and future initiatives. Application of reversible lanes using movable barrier provides a significant amount of flexibility as shown in the next sections.

Table 12. Minimum Directional Split Requirement for Contraflow Lane Application on a Freeway		
Number of Lanes (total,both directions)	Percentage Traffic in Off-Peak Direction	Percentage Traffic in Peak Direction
4	33	67
6	40	60
8	43	57
10	44	56

Note:
The directional split calculation assumes 2,000 vehicles per hour per lane in the peak direction (at capacity) and the same for the with-flow lanes in off-peak direction once a lane is reversed in the off-peak direction for a minimum directional split calculation. The minimum directional split is the lowest directional split necessary for the reversal of the traffic flow on the median lane of the off-peak side not to cause any congestion on the with-flow lanes on the off-peak side.
For example, for a 6-lane freeway (3 lanes per direction) the volume on the peak side is 3 x 2,000 = 6,000 vehicles per hour. On the off-peak side, it is assumed the median lane traffic flow is reversed. The remaining two lanes will carry a volume of 2 x 2,000 = 4,000 vehicles. The directional split is therefore 4,000/10,000 = 40% on the off-peak side and 60% on the peak side.

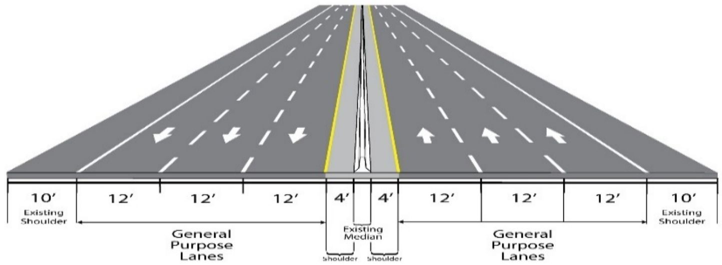
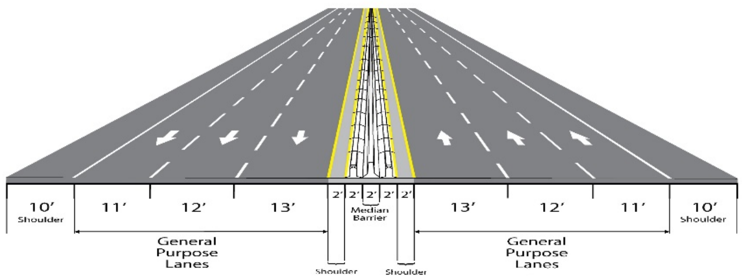
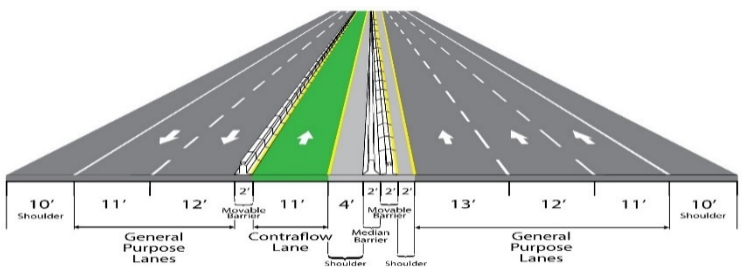
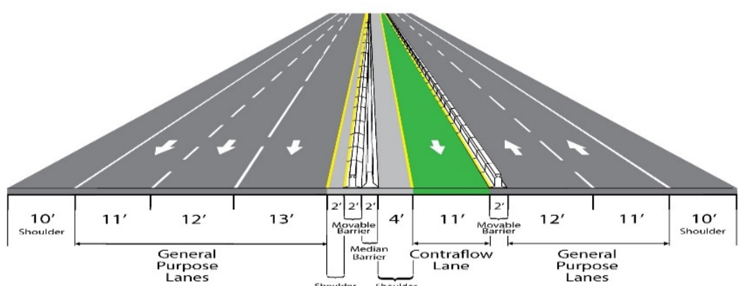
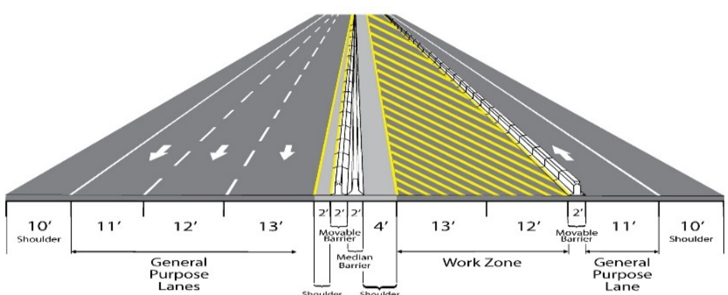
3.2 Illustrations on Flexibility Provided by Reversible Lanes Using Movable Barrier

Tables 13 to 16 on the following pages provide illustrations on how movable barriers can be applied to address congestion on urban freeways.

Notes about Tables 13-16:

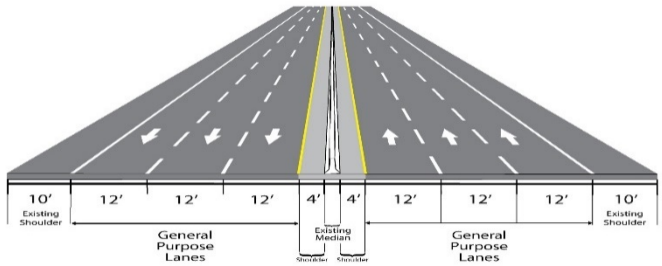
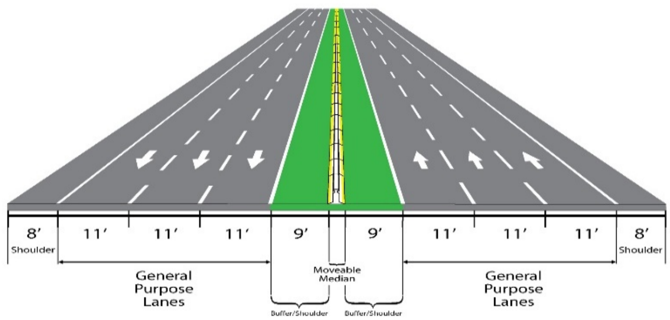
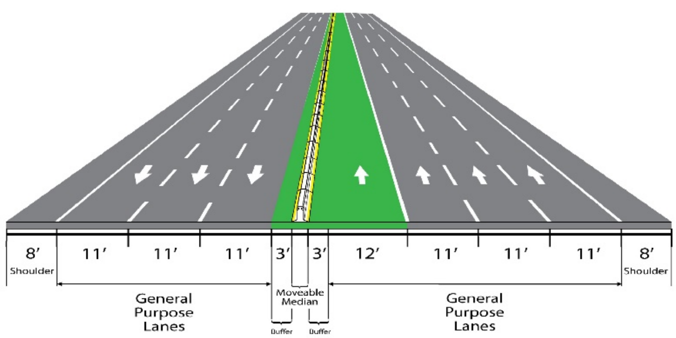
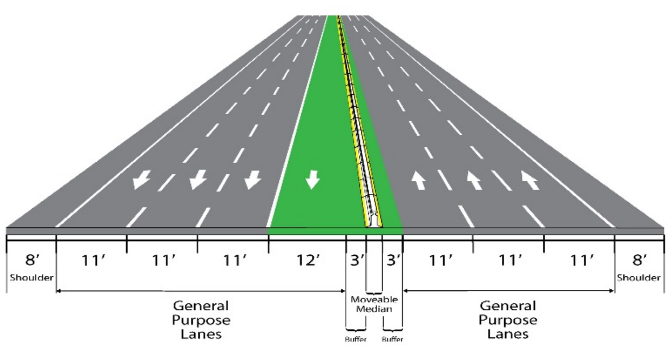
1. Green generally indicates additional lanes provided by the movable barrier system.
2. The application of a movable median can be simplified by designing freeway overpasses without median columns. If median columns are present, a go-around can be applied but it increases operational time and narrows outside shoulders for a limited distance. The longer span required will increase the depth of the girders which can impact access to driveways adjacent to the road crossing the freeway.
3. The benefit in providing an additional (third) HOT lane in the peak direction as provided for in Table 15 might or might not increase revenue. If toll elasticity is higher than -1.0 then the revenue will most likely increase when the toll rate is reduced to attract additional toll-paying vehicles. If the elasticity is less than -1.0 then most likely there will not be a toll revenue increase.
4. Where the number of HOV vehicles that do not have to pay toll when using the HOT lanes is high, then a third HOT lane will come in handy. An additional peak-period lane will also benefit an existing HOT facility where there is only one HOT lane per direction.

3.2.1 Contraflow System

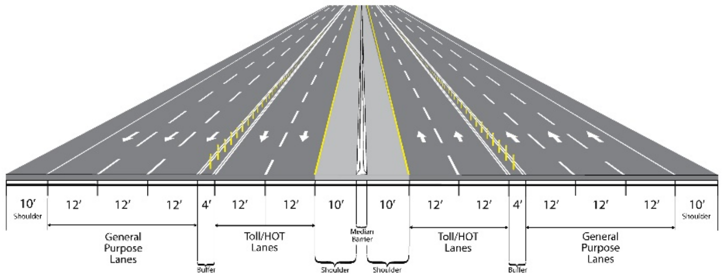
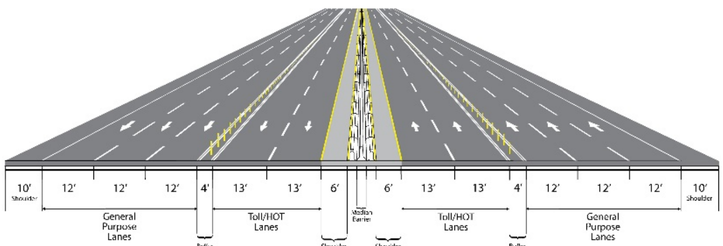
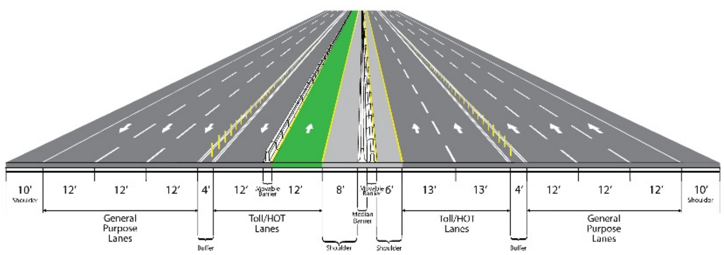
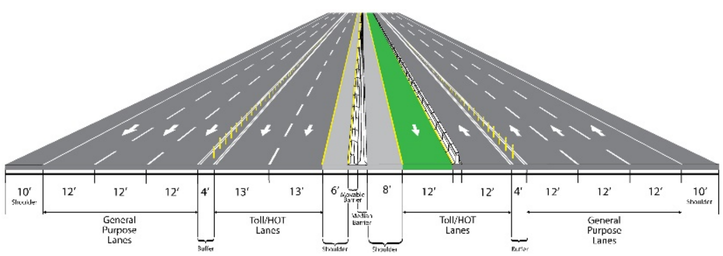
<table>
<tr><th colspan="3">Table 13. Flexibility Provided by Contraflow System Using Movable Barrier</th></tr>
<tr><td>Typical Cross Section Before Implementation of Contraflow Lane System</td><td></td><td>A typical urban freeway cross section is assumed with 4 ft. inside shoulders, 12 ft. lanes and 10 ft. outside shoulders.</td></tr>
<tr><td>Contraflow System
Movable barrier in neutral position.</td><td></td><td>Both movable barriers are placed next to the fixed median barrier during the off-peak periods.</td></tr>
<tr><td>Contraflow System Option 1:
Provide one additional lane in a.m. peak period direction. Two lanes can also be provided depending on directional split.</td><td></td><td>For the implementation of the contraflow lane system, only restriping is necessary between crossover points including the lengths of the crossover points.</td></tr>
<tr><td>Contraflow System Option 2:
Provide one additional lane in p.m. peak period direction. Two lanes can also be provided depending on directional split.</td><td rowspan="2"></td><td>Depending on traffic characteristics, a contraflow lane can be added to the a.m. peak direction or the p.m. peak direction, or both.</td></tr>
<tr><td>Contraflow System Option 3:
Use movable barrier system to open and close a work zone to minimize traffic disruption.</td><td>One or two lanes can be opened or closed with the movable barrier. This option can be particularly helpful along bridges and tunnels where shoulders are often non-existent or extremely narrow.</td></tr>
</table>

3.2.2 Movable Median System

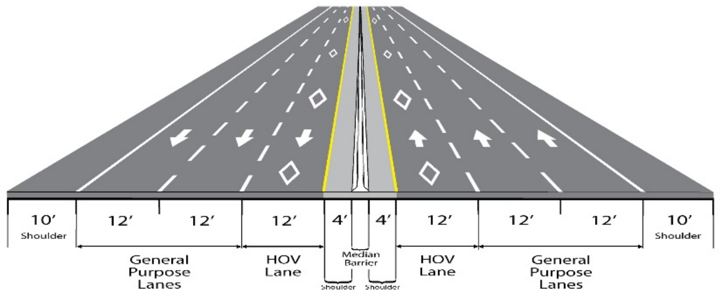
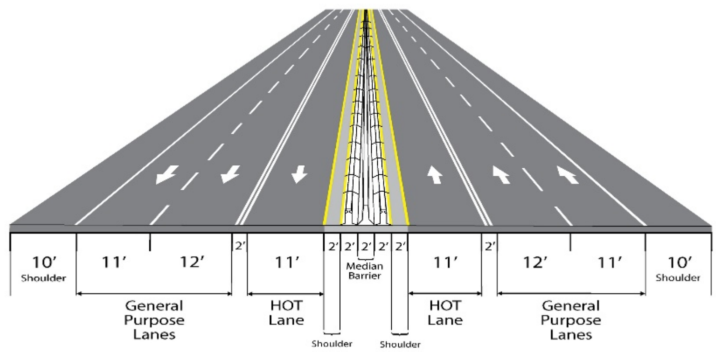
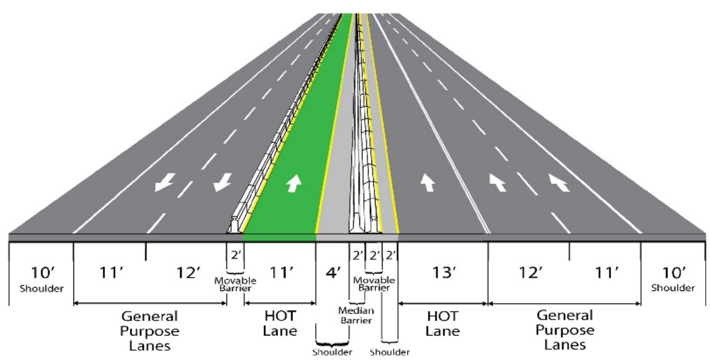
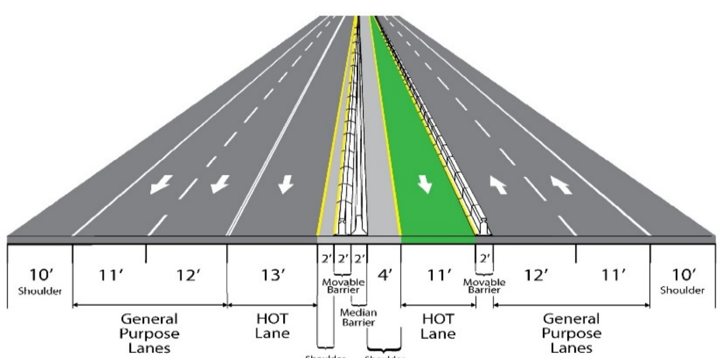
Table 14. Flexibility Provided by a Movable Median System Using Movable Barrier

Typical Cross Section Before Implementation of a Movable Median System		A typical urban freeway cross section is assumed with 4 ft. inside shoulders, 12 ft. lanes and 10 ft. outside shoulders.
Movable Median System Movable barrier in neutral position.		For the implementation of the movable median system on an existing freeway, a fixed median barrier, light standards, signs and stormwater provisions might have to be removed. In addition, restriping of lanes might be necessary. A work-around is available for median columns, but requires additional operations. Because of the high level of flexibility provided by a movable median, where possible, the placement of utilities in the median should avoided.
Movable Median System Option 1: Provide one additional lane in a.m. peak period direction. Two lanes can also be provided depending on directional split.		The movable barrier can be moved to create two lanes in the peak direction if required.
Movable Median System Option 2: Provide one additional lane in p.m. peak period direction. Two lanes can also be provided depending on directional split.		A movable median provides significant flexibility to address changes in traffic flow over time, and can allow reasonable capacity to be maintained during major incidents, and maintenance.

3.2.3 HOT Managed Lane System with Contraflow Lanes

Table 15. Flexibility Provided for HOT Managed Lanes by Using Movable Barrier to Provide a Contraflow Lane System within HOT lanes		
Typical Cross Section Before Implementation of Contraflow Lane System within HOT Lanes		A typical urban freeway with HOT lane cross section.
Contraflow Lane System in neutral position		The neutral position will typically be in place during off-peak times.
Contraflow Lane System Option 1 Provide one additional HOT lane in a.m. peak period direction.		Providing an additional HOT lane during a peak period will allow the lowering of toll charges to draw more traffic to the HOT lanes which in turn will reduce congestion. The impact on toll revenue will depend on the price elasticity of drivers.
Contraflow Lane System Option 2: Provide one additional HOT lane in p.m. peak period direction.		The provision of the movable barrier will allow more options to address incidents and capacity reduction due to maintenance.

3.2.4 HOT Managed Lane System Created by Using Existing HOV Lanes

<table>
<tr><th colspan="3">Table 16. Flexibility by Movable Barrier to Provide a Viable HOT Managed Lane System Using Existing HOV Lanes to Operate as Contraflow and With-Flow Lanes</th></tr>
<tr><td>Typical Cross Section Before Implementation of a Movable Barrier System</td><td>
</td><td>A typical urban freeway cross section is assumed with 4 ft. inside shoulders, 12 ft. lanes and 10 ft. outside shoulders.</td></tr>
<tr><td>HOT Managed Lane System in Neutral position (off-peak)</td><td>
</td><td>The conversion of existing HOV lanes to HOT lanes and the application of the movable barrier to create two HOT lanes operating in the peak direction has potential for revenue stream requiring minimal capital costs.</td></tr>
<tr><td>HOT Managed Lane System Option 1
Provide one additional HOT lane in a.m. peak period direction.</td><td>
</td><td>For the implementation of the contraflow lane HOT lanes, only restriping is necessary. Plastic pylons might be necessary to prevent general purpose lane vehicles from moving in and out of the HOT lanes.</td></tr>
<tr><td>HOT Managed Lane System Option 2
Provide one additional HOT lane in p.m. peak period direction.</td><td>
</td><td>The conversion of HOV lanes to HOT lanes using the movable barrier will allow toll pricing to make carpooling more attractive if high occupancy vehicles are allowed to use the HOT lanes free of charge.</td></tr>
</table>

4. Flexibility and Highway Design

Tables 13 to 16 provides illustrations showing how the movable barrier system can be applied to reduce congestion on urban freeways. As can be seen, there are many variations in the application of the movable barrier system.

One of the most flexible configurations is illustrated in Table 14 with the movable barrier operating as a movable median. Movable median application can also be applied with two movable barriers running parallel to each other. This provides further possibilities such as a central, barrier separated reversible managed lane (one or two lanes), and can operate as an HOV lane or an HOT lane.

When an urban freeway is reconstructed or when a new freeway is constructed, the accommodation in the design of a movable median will significantly increase the ability to respond to unforeseen future circumstances. In accommodating a movable median, there should be no or limited median obstructions, particularly bridge columns. Lateral grades, storm water management, and the placement of light standards and signs should also be taken into consideration. A further consideration is the increase in the depth of girders when the span of the girders increases. For example, a span of 150 feet might require a girder depth of 6 feet. This might require some re-grading of cross street approaches to a bridge.

All considered, a design that can eliminate median columns and enhance the application of a movable median system will ensure that the freeway will be able to function optimally many more years in future than a conventionally designed inflexible freeway.

What is also of note is that the “green” lanes in Figures 13-16 are ideal lanes for the accommodation of express bus service and/or the accommodation of autonomous vehicles during the initial stages of deployment.

5. New California Legislation

On September 23, 2016, the California state legislature passed Bill AB 2542 that requires, prior to the California Transportation Commission (CTC) approving a capacity-increasing project or major street or highway lane realignment project, the California Department of Transportation (Caltrans) or a regional transportation planning agency must demonstrate that reversible lanes were considered for the project.

The legislature provided the following further comments during hearings:

- Reversible lanes add peak-direction capacity to a two-way road and decrease congestion by "borrowing" available lane capacity from the other (off-peak) direction. The lanes are particularly beneficial where the cost to increase capacity is especially expensive, like on bridges and in dense urban areas.
- Reversible lanes are not new to California. In fact, reversible lanes were first inaugurated on the Golden Gate Bridge in October 1963. While they worked to reduce serve traffic in the peak direction, they were labor intensive to operate and posed serious safety problems because they led to the increase in head-on collisions. Now the lanes are adjusted with the aid of a "zipper"-a moveable barrier machine that transfers a heavy concrete and metal barrier across one lane and related labor and safety problems have been minimized. Today, in addition to the Golden Gate Bridge, reversible lanes are used on the San Diego-Coronado Bridge, Interstate 15 in San Diego, and, until recently, in the Caldecott Tunnel (in California). Furthermore, the use of reversible lanes is increasing, for example, during large sporting events, traffic incidents, construction, and evacuations.

- According to the Texas A&M Transportation Institute (TTI), the decision to consider reversible lanes is usually based on the need to mitigate recurrent congestion. Reasons agencies give for using reversible lanes include: congestion mitigation, queue length, the need to decrease travel time, and the need to improve the overall corridor level of service. TTI asserts that planning of specific reversible facilities does not differ substantially from conventional facilities. It also suggests that "the vast majority of reversible lanes are implemented on lanes not originally planned or designed for bi-directional use. Most reversible lanes are incorporated into conventionally designed roadways that were later reconfigured for permanent or periodic flow conversions using various permanent or temporary design and control features. The exceptions to this case are applications on freeways, in particular freeway high occupancy vehicle (HOV) and transit reversible lanes, where transition termini and lane separations are planned, designed, and constructed specifically for the purpose of a reversible lane."