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Guidelines for the Implementation of Flipped Left Diamond Interchange (FLDI) Design

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16.Abstract

The Flipped Left Diamond Interchange (FLDI) with frontage roads offers several operational benefits. It eliminates conflict points between opposing left-turn movements by flipping the left-turn lanes in opposing directions, allowing simultaneous left-turn movements and improving traffic signal efficiency. FLDI with frontage roads maintains connectivity between frontage roads, which enhances through movements and access to corner properties. Additionally, it significantly reduces vehicle delays, queue lengths, and the number of stops under heavy traffic conditions. FLDI is cost-effective, as it can be implemented within the existing right of way without major construction, making it a practical solution for improving traffic operations at diamond interchanges. This paper develops guidelines for operationally effective FLDI based on research and existing roadway design guidelines. In developing these guidelines, both operational and safety performances were considered.

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Guidelines for the Implementation of FLDI Design

This study aims to develop guidelines for operationally effective flipped left diamond interchanges based on the results of this research and some existing roadway design guidelines. In developing these guidelines, both operational and safety performances were considered. The recommended guidelines were provided in shaded text boxes for easy reference.

Applicable Conditions

Guideline 1 – Applicable Conditions for Implementing the FLDI design

Flipped left diamond interchange can operate efficiently at the freeways with frontage roads and where the level of service (LOS) is worse than C.

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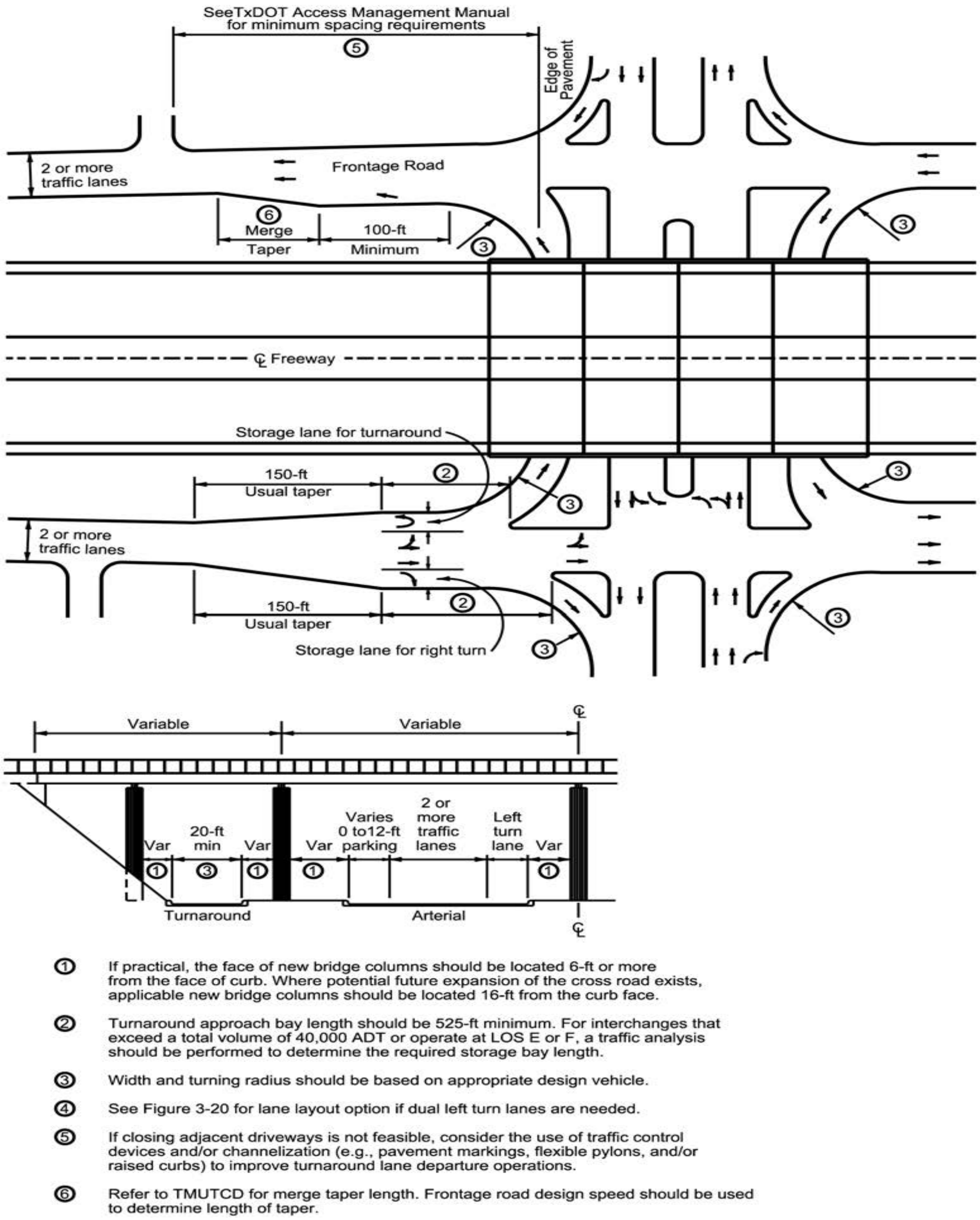

Figure 1: Typical Diamond Interchange with Frontage Road (Source: TxDOT Roadway Design Manual, Figure 15-33; p15-39)

FLDI can reduce vehicle delay by more than 30% compared to the conventional diamond interchange in locations with heavy traffic volumes. By comparing those delays in with the LOS criteria for interchanges with signalized intersections in Highway Capacity Manual 6th Edition in Chapter 23 (see Table 1), it is evident that FLDI should be implemented where the level of service is worse than C.

Table 1: LOS Criteria for Interchanges with Signalized Intersection

Average Control Delay (s/veh)	Level of Service (LOS)
0-10	A
> 10 - 20	B
> 20 - 35	C
> 35 - 55	D
> 55 - 80	E
> 80	F

Geometric Design and Traffic Control for FLDI

Guidelines 2 to 4 are about the geometric design and traffic control strategies for FLDI design. Figure 2 illustrates the layout of the FLDI with frontage roads. In this figure, the target areas for different guidelines are indicated.

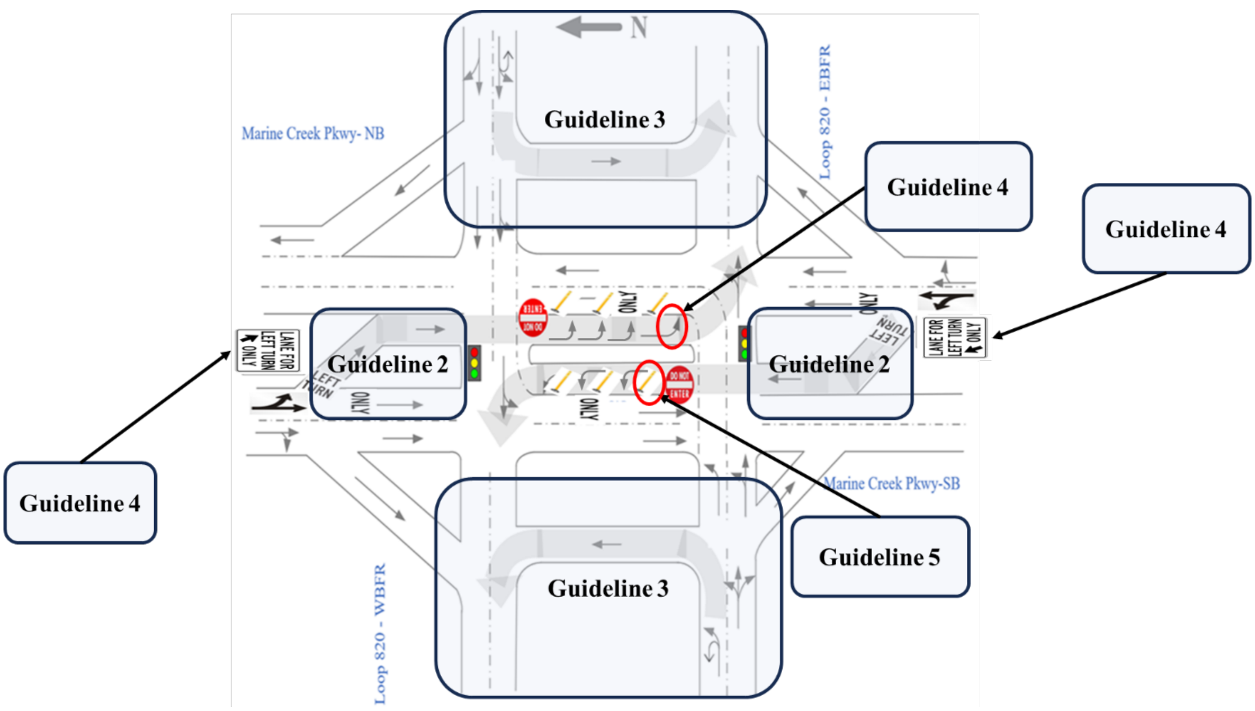

Figure 2: Layout of Flipped Left Diamond Interchange with Frontage Roads

Guideline 2 – Storage length and deceleration length of the flipped left turn lanes:

Storage length: As mentioned in Guideline 1, the flipped left diamond is suitable for high-traffic volume areas. Thus, signalized interchange operation must be considered rather than STOP control interchange operation. In that context, the conventional rule of thumb method for signalized intersection should be used. It estimates the storage requirements of left-turn lanes based on the average left-turn volume per cycle for signalized intersections. A general form of the rule of thumb methods can be expressed mathematically by the following equation:

$$L = K\left(\frac{V}{N_C}\right)S$$

where L = storage length (ft), V = left-turn flow rate during the peak hour (vph), K = a constant to reflect random arrival of vehicles (usually 2), N_C = number of cycles per hour, S = average queue storage length per vehicle (average distance, front bumper-to-bumper of a car in queue, see Table 2)

Deceleration length: Table 3 provides recommended deceleration lengths for left-turn lanes.

This guideline is based on the TxDOT Roadway Design Manual (revised November 2024), New Location and Reconstruction (4R) Design Criteria Section 2- Urban Streets in Chapter 3. Figure 3 illustrates the storage length and deceleration length for left-turn lenses.

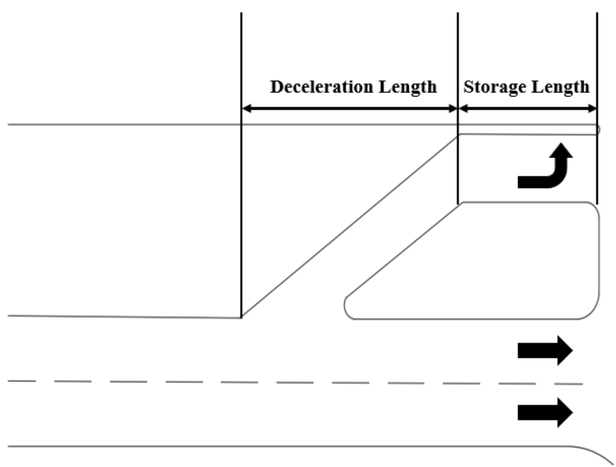

Figure 3: Storage Length and Deceleration Length for Left Turn Lanes

In the TxDOT Roadway Design Manual, the rule of thumb method has been recommended for calculating the storage length of left-turn lanes as shown in the following equation:

$$L = K\left(\frac{V}{N_C}\right)S$$

Where,

- K = 2 (the probability of storing the longest expected queue is greater than 0.98).
- S is determined based on the percentage of trucks as given in Table 2.

Table 2: Queue Storage Length (per vehicle) Based on Percentage of Trucks

% of Trucks	S (ft)
< 5	25
5 – 9	30
10 – 14	35
15 – 19	40

In addition, a minimum storage length (100 ft) is set up for the intersection with very low left-turn traffic volume. Finally, the storage length for the left-turn lane is determined by the following equation:

$$L^* = \max\,(100ft, L)$$

where L is determined by the equation described above based on the traffic.
The guideline for deceleration length is directly from the TxDOT roadway Design Manual.

Table 3: TxDOT Standards for Deceleration Lengths in a Left-Turn Lane (ft)

Design Speed (mph)	Single Left Turn Lane				Dual Left Turn Lanes	
	Deceleration Length[1] (ft) Speed Differential[2]			Taper Length (ft)	Deceleration Length[1] (ft)	Taper Length (ft)
	None	5-mph[3]	10-mph[4]			
30	150	105	70	50	150	100
35	205	150	105	50	205	100
40	265	205	150	50	265	100
45	340	265	205	100	340	150
50	415	340	265	100	415	150
55	505	415	340	100	505	150
60	600	505	415	100	600	150

Notes:

1. Based on 6.5 ft/s^2 deceleration to stopped condition throughout the entire length. Larger deceleration rates may be used when deceleration lengths based on 6.5 ft./s^2 are impractical.
2. Speed differential = the difference between the assumed speed of a turning vehicle at the moment when it arrives at the taper and the design speed of the roadway.
3. Based on 6.5 ft/s^2 deceleration from 5 mph less than design speed to stopped condition throughout the entire length.
4. Based on 6.5 ft/s^2 deceleration from 10 mph less than design speed to stopped condition throughout the entire length.

In the TxDOT Roadway Design Manual, deceleration length, with no speed differential, as shown in Table 3, assumes that deceleration starts at the beginning of the taper and continues to a stopped condition. Where providing this deceleration length is impractical, it may be acceptable to assume that turning vehicles will begin decelerating before arriving at the taper and clearing the through traffic lane. See Table 3 for 5 mph and 10 mph speed differential deceleration lengths under this assumption.

Guideline 3 – U-turns and left-turns from the frontage roads.

- A dedicated U-turn Lane for the traffic on the frontage roads needs to be provided.
- A “Do Not Enter” traffic sign should be installed to prevent left-turn vehicles from the frontage road from entering the flipped left-turn lanes.
- Pavement markings of turning guidelines for the left-turn vehicles from the frontage road should be provided.

This guideline is based on the TxDOT Roadway Design Manual (Revised December 2022), New Location and Reconstruction (4R) Design Criteria Section 6- Freeways in Chapter 3 and MUTCD 11th Edition, Regulatory Signs, Barricades and Gates Section 2B.46 DO NOT ENTER sign (R5-1) in Chapter 2B. The corresponding section of this guideline is illustrated in Figure 2. As discussed in Chapter 3, a dedicated U-turn Lane for the traffic on the frontage roads needs to be provided. It is because if the vehicles from the frontage roads enter the flipped left-turn lanes (FLTLs) to make a U-turn, the left-turn vehicles that follow them will also enter the FLTLs. Then, they will be trapped and forced to make U-turns, which may cause safety problems. To prevent such a problem, a “Do Not Enter” traffic sign should be installed to prevent any left-turn /U-turn vehicles from the frontage roads from entering the FLTLs. Meanwhile, dedicated U-turn Lanes need to be provided for the U-turn vehicles on the frontage roads. In addition, to prevent the left-turn vehicles on the frontage roads from entering the FLLT accidentally, pavement markings of turning guidelines for these left-turn vehicles should be provided.

Guideline 4 – “Left Turn Only” traffic signs and pavement markings must be installed.

The Mandatory Movement Lane Control signs (Figure 4) shall be located in advance of the intersection, such as near the upstream end of the mandatory movement lane and/or at the near side of the intersection where the regulation applies.

This guideline is based on MUTCD 11th Edition, Section 2B.27 Intersection Lane Control Signs in Chapter 2B. The corresponding section of this guideline is illustrated in Figure 2.
“Left Turn Only” traffic signs and pavement markings need to be placed at the entrances of the left-turn channels to guide the left-turn vehicles from the arterial to enter the FLTLs. According to MUTCD:

- A Mandatory Movement Lane Control sign (R3-7L in Figure 4) should be accompanied by lane-use arrow markings, especially where traffic volumes are high, a high percentage of commercial vehicles, or other distractions exist.
- Where a mandatory left is added at a median location, a LANE FOR LEFT TURN ONLY (R3-19 in Figure 4) sign may be post-mounted on the median at the beginning of the taper (In this case, the beginning of the channel should be considered).

R3-7L R3-19

Figure 4: Left Turn Only Traffic Signs (Source: MUTCD 11th Edition, Figure 2B-4; p90-91)

Guideline 5 – Yellow tubular markers must be installed to separate opposing traffic.

- Channelizing devices such as tubular markers may be used for general traffic control purposes, such as emphasizing separate traffic flows in the opposite direction.
- Tubular markers for permanent installations shall be a minimum of 28 inches in height and shall be a minimum of 2 inches wide facing road users.

This guideline is based on MUTCD 11th Edition, Section 3I.01 Channelizing Devices and Section 3I.02 Tubular Markers in Chapter 3I. The corresponding section of this guideline is illustrated in Figure 2.

Section 3I.01 describes the color used for channelizing devices. It should emphasize pavement marking patterns except orange, which is used for temporary traffic control. According to MUTCD, the standard is that channelizing devices shall be retroreflective or internally illuminated. The device used for channelizing shall be yellow if the device separates traffic flows in opposite directions (Part 07, Section 3I.01). So, yellow-colored tubular markers are considered for separating the flipped left turn movement and opposing through movement in FLDI design. An example of a tubular pavement marker is shown below in Figure 5.

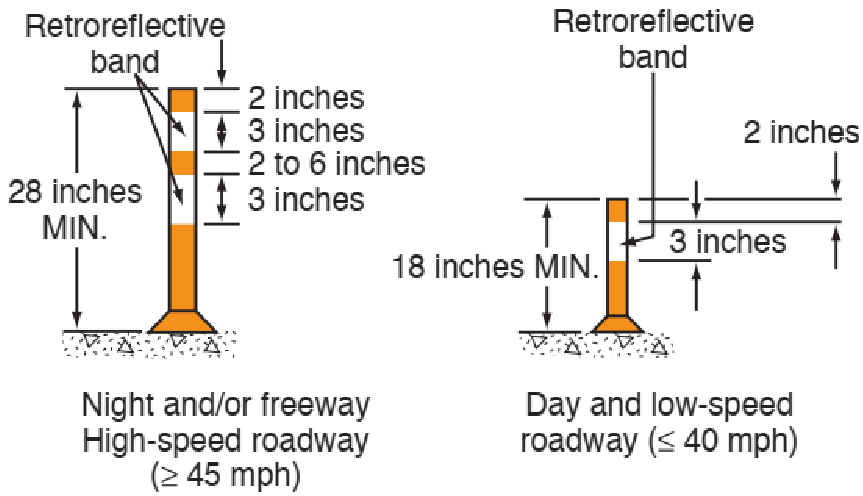

Figure 5: Example of Tubular Markers (Source: MUTCD 11th Edition, Figure 6K-1; p816)

<u>Guideline 6 – Recommended FLDI Signal Timing Plan for FLDI.</u>

A lead-lag signal timing plan, as shown in Figure 7, is recommended for the FLDI with frontage roads. This phasing plan should consider the left turn traffic progression time between the two intersections at the diamond interchange. Thus, it will prevent the green starvation problem at the downstream intersection for the left turning movements.

This guideline addresses two issues in the signal timing strategy for FLDI with frontage roads. Firstly, to ensure the safe operation of this new design, a protective-only left-turn operation mode is recommended. Secondly, the signal phasing plan should consider the progression time between the two intersections. Otherwise, it could create a green starvation problem at the downstream intersection for the left turning lanes (where green time is wasted because of a lack of arrival traffic from the upstream intersection). In Figure 6, the FLDI Design layout with phase numbering has been shown. If signals for phases 9 and 5 turn green at the same time, it takes a travel time for the left-turn vehicles to arrive at the downstream intersection. In this way, the green time for phase 5 at the downstream intersection will be wasted. Therefore, an offset between phases 9 and 5 needs to be set to consider the progression time between the two intersections.

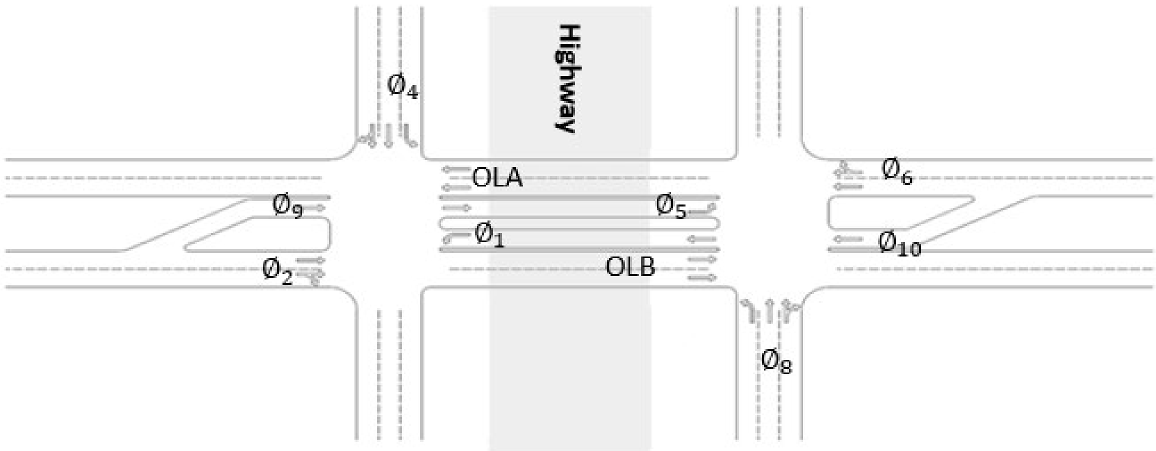

Figure 6: FLDI with Frontage Road Design Layout with Phase Numbering (Source: Mozdbar, 2020)

To consider the traffic progression timing between the two intersections, a new signal phasing plan has been developed. Figure 7 shows the signal timing plan designed for FLDI, where phase 9 starts before the start of phase 5. In this way, the left-turn vehicles can be released from the upstream intersection before they arrive at the downstream intersection, where the left-turn signal will turn green at the time they arrive. The offset between Phase 9 and Phase 5 ($\emptyset_{9\_5}$) can be calculated by the following equation.

$$\emptyset_{9\_5} = Travel\ Time\ From\ Left\ to\ Right\ - Ag \quad (1)$$

Where, *Ag* is the advanced green time, which is proposed to prevent vehicles from making unnecessary slowdowns or stops. Based on a previous study by Chaudhary et al. (2000), *Ag* is assumed as 2s. For the same progression request, Phase 10 also needs to start before the start of Phase 1. In the proposed signal timing plan in Figure 7, since Phase 1 is the lagging left-turn phase, it starts right after Phase 2. Thus, the offset between Phase 10 and Phase 1 is equal to the signal time split (in seconds) for Phase 2. If Phase 2 is longer than the required progress time between two intersections, the left turns need to wait at the downstream intersection for a few seconds before the green light turns on. If not, Phase 2 needs to be extended to the required progress time between two intersections. Thus, the offset between Phase 10 and Phase 1 ($\emptyset_{10\_1}$) can be calculated by the following equation.

$$\emptyset_{10\_1} = Max\ (travel\ time\ From\ Right\ to\ Left\ - Ag, \emptyset_2)$$

Where $\emptyset_2$ is the original signal time split for Phase 2 calculated based on the traffic volume (in seconds).

In the proposed lead-lag signal timing plan, the leading phase between Phase 5 and Phase 1 should be decided according to the traffic volume. Whichever left turn phase has greater volume should be considered the leading phase. In Figure 7, beside the two offsets ($\emptyset_{9\_5}$ and $\emptyset_{10\_1}$), the overall signal timing splits between different phases should be calculated according to the traffic counts collected at this interchange.

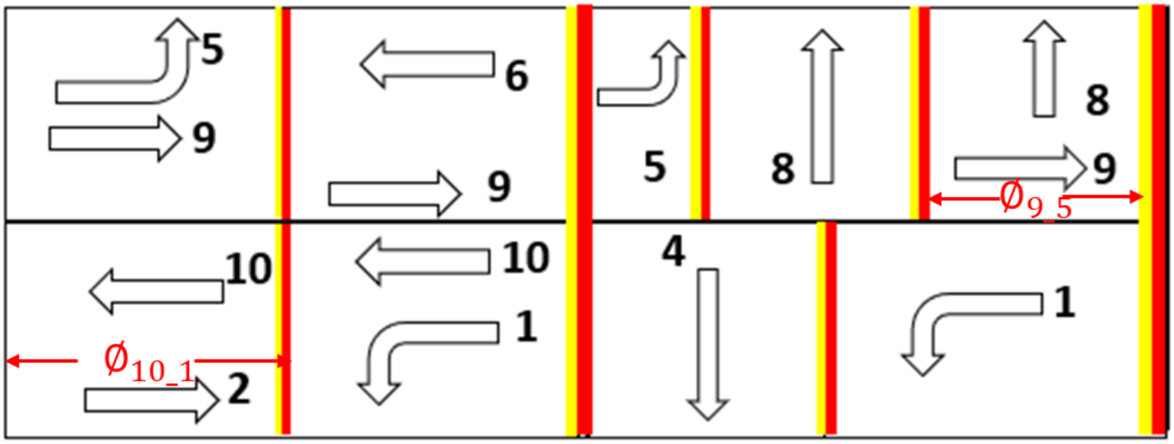

Figure 7: Recommended FLDI Signal Timing Plan

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