Temporary Traffic Control and Work Zones

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Construction Work Zone Objectives

- Safety
- Constructability
- Mobility
Mobility

• Moving road users efficiently through and around a work zone with minimum delay and without compromising safety

Source: ITE Traffic Engineering Handbook, Ch 15

Constructability and Maintainability

• **Constructability**: Maximizing the ability to complete project work while optimizing efforts, materials and costs needed to protect public traffic and workers adequately.

• **Maintainability**: Using maintenance history, knowledge and experience to optimize project design and maximize product service life.

Source: ITE Traffic Engineering Handbook, Ch 15; ODOT
**Work Zone Measures to Implement Traffic Control Plan (TCP)**

- TCP safely and efficiently routes Road Users through and around the work zone by:
  - Using temporary reflective signs and safety appurtenances.
  - Using devices to highlight appropriate pathways.
  - Maintaining design and operational characteristics similar to permanent roadway environment.
  - Avoiding frequent or abrupt changes in roadway geometry.
  - Avoid work zone conditions resulting in unanticipated changes in traffic speeds or large speed differentials.

* Strictly controlled operations on well-defined pathways


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**Work Zone Safety**

- Use same basic safety operations, design and control principles as for permanent roadways and roadsides

* Work zones are “permanent”, i.e., “always there”
**Temporary Traffic Control Measures**

- **Traffic Control Measures** = Strategies for managing traffic and allowing efficient construction
  - **EXAMPLE:** Remove (detour) traffic from work zone to maximize construction efficiency and safety
  - **EXAMPLE:** Flagging vs. temporary traffic signal
  - Avoid excessive out-of-direction travel, delay and inconvenience.
  - Work with Emergency Response agencies, school districts, postal carriers, etc, to determine maximum allowable delays
  - Maintain reasonable access for residents & private businesses

  * Minimize impact to local activities, businesses and residents

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**Work Zone Crashes**

- Work zone crash experience provides a framework for Traffic Control Plan (TCP) design
  - Defines need for driver guidance based on crash type, number, severity and location
  - In work zone crashes, drivers and passengers are 15 times* more likely to be killed or injured versus workers.

  * Approximate. From 2000-2015 Statewide Oregon data

*Sources: NCHRP #600, p. 13-2; ODOT*
**General Crash Characteristics**

- 58% of all fatal work zone crashes* are fixed object collisions
- Typical Crashes:
  - Male driver, 25-34 yrs
  - Clear weather, during mid-afternoon
  - Slow or stopped work zone traffic
  - Fixed object and rear-end collisions
- 25% of all work zone fatal crashes involved a large truck**

* 2013 GES and FARS data
** National 2000 – 2008 data, compared to 12% for all fatal crashes

*Source: FHWA Work Zone Safety - Statistics*

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**General Crash Characteristics**

- Crash Locations*:
  - 23% of work zone fatal crashes occurred on Interstates, 20% on urban arterials.
  - Combined 43% of work zone fatal crashes occurs on only 5% of national roadway network
- Fewer crashes at night because volumes are lower; but crashes increase
  - With closed lanes, and
  - With significant traffic queues

* 2014 national data, 607 work zone fatal crashes

*Source: FHWA Work Zone Safety - Statistics*
Work Zone Crash Characteristics

- Work zones are particularly hazardous to motorcyclists:
  - 1997: 6.5% of fatal work zone crashes
  - 2007: 10.5% of fatal work zone crashes

* Even though only 3% of registered vehicles

Source: Workzonesafety.org

General Crash Characteristics

- Crashes typically increase by 20-30% in work zones compared to normal crash experience at the site
- “Activity area” location of most work zone crashes
- “Truck involved crashes” in “activity area” create most injuries

Source: NCHRP #600, p. 13-2
Critical Human Factors in Work Zones

- Physical human factors taxed more in work zones than normally;
  - Vision
    - Unusual & untypical information, conditions & operations are present
  - Visual acuity
    - Both static & dynamic are important with numerous unique elements and conflicts
  - Nighttime vision
    - Lower illumination results in poor vision
    - Glare more severe
  - Glare sensitivity of construction lighting vs. natural lighting with sources
    - Traffic signals
    - Oncoming headlights, surroundings
    - Sun position

Critical Human Factors in Work Zones (cont)

- Cognitive and psychological functions
  - Analytical ability
    - Limited by complexity and uniqueness
  - Driver familiarity
    - Limited experience with work zone activity
  - Decision-making
    - Based on driver’s goals and values
  - Expectancy
    - Based on experience, expectations, habits, training

  * Impacted by weather and traffic conditions
Critical Human Factors in Work Zones (cont)

• Sight distance
  – Aggregate result of numerous human factors
• Important “sighting” distances
  – Emergency sight distance
    • PRT 1–2.5 s; \( a = 11.2 \) to (MAX\( a \))
  – Stopping sight distance
    • PRT 2.5–5 s; \( a = 11.2 \) FPS\(^2\)
  – Decision sight distance
    • Adds PRT maneuver time for complexity
  – Pavement sight distance
    • SSD with height of object = 0

Car Following Paradox

• In work zones:
  – As vehicle speeds increase, time gaps between cars decrease
    • i.e., drivers tailgate slower moving vehicles
  – Even though it takes longer to stop at higher speeds

Source: NCHRP #600, p. 13-2
**Traffic Operations in Work Zone Platoon**

- Desire to keep the traffic platoon moving slowly
- Construction vehicles should not be in the platoon
  - Their exit from platoon unexpected
  - Their entry into platoon is conflict
  - Objectives of public traffic and contractor are different

**Speed Reduction and Speed Limit**

- If temporarily reducing regulatory speed limit, avoid reductions of 20 mph or more
  - Common: 10–15 mph reductions
  - Less common: 20 mph reductions done in two 10 mph steps
- Mean vehicle speed reductions are most common where:
  - Speed limit is not reduced
  - Speed limit is not reduced more than 10 mph
- Least increase in speed variance, relative to upstream, occurs with speed limit reductions up to 10 mph

*Source: NCHRP #600, p. 13-12*
Increase in Speed Variance from Upstream into Work Zone

% Increase in Speed Variance

Source: NCHRP #600, p. 13-12

Safety Impacted Least with 10 mph Regulatory Work Zone Speed Reductions

% Increase in Fatal + Injury Rates

Source: NCHRP #600, p. 13-12
Vehicle Speed Affected by Lane Width & Number of Lanes

- Speed reductions related to lane width
  - 11-ft lanes: observed speed reduction of 4.4 mph
  - 10.5-ft lanes: observed speed reduction of 7.2 mph
- Speeds also correlated with number of open lanes
  - Some additional effect seen based on shoulder widths

Sources: NCHRP #600, p. 13-13; ODOT

Speed Control in Work Zones

- Most effective tools in controlling speeds
  - Combination of traffic control devices – examples include:
    - Channelization devices @ 40 ft spacing or less
    - Temporary concrete barrier 2-4 ft from edge of traffic lane
    - Non-linear temporary alignments
    - Radar speed trailers (e.g. “YOUR SPEED IS ___”)
  - Single most effective tool: staffed police car
    - Placed in advance of transition zone
    - Flashing lights on (may depend on enforcement agency policy)

Sources: “Meeting Customer’s Needs for Mobility and Safety During Construction and Maintenance Operations,” FHWA, HPQ-98-1, Sept 1998; ODOT
Traffic Impact Analysis: Congestion

- Traffic prediction and impact analysis methods
  - Can estimate traffic conditions:
    - Traffic volumes
    - Free flow traffic conditions
    - Capacity and service volumes
    - Delay estimates
    - Queue lengths

Source: “Oregon’s Web-Based Work Zone Traffic Analysis (WZTA) Tool”, Fall 2010

Critical Human Factors for Safety in Work Zones

- Driver work load & working memory capacity
- Cognitive limits
  - Mental acuity or alertness
  - Level of fatigue
  - Cerebral or emotional distractions
- Decision making ability
  - Related to Cognitive limits, or
  - Driver experience level
Critical Measures of Human Factors Impacts

- Perception-Reaction Time (PRT)
- Acceptable deceleration
- Speeding and speed control
- Car following characteristics
- Driver experience, reaction, knowledge and familiarity
- Sight distance

Primary Way to Achieve Traffic Control

- Focus on “work zone information and control”
  - Warning of upcoming work
  - Slowing of traffic by signing
  - Move traffic over
  - Stop or slow traffic
**Information Processing Problems**

- Driver samples inappropriate inputs or processes inputs too slowly  
  - e.g., unneeded detail, unnecessary information  
  - Not standard; non-work zone signs
- Work load too great and overload handled by ignoring part of demand (information) input  
  - e.g., focus on that information that is more important

**The Balanced Performance**

![Graph showing the balanced performance between input/information and output performance (driver decisions) with points A, B, C, and D]
**The Balanced Performance**

- Up to A, the driver outputs decisions at rate matching input of information
  - Like a low volume, moderate speed rural road, also freeway work zones
- Up to A, all information is processed correctly
- Overload of information inputs is handled by shedding some less important inputs
  - Conversation with others, increasing work zone traffic, or congestion around a curve

**Overloaded Driving Task Model**

- As demand input information processing increases, beyond A, the output (decision-making) though increasing, falls behind demand to process information
- As a result, a gap between input and output occurs
  - Driver’s output continues to increase but doesn’t match input, up to B
  - Driver’s output (of decision-making) falls away due to information overload to C
- For a driver who has been significantly overloaded, a residual effect occurs even after the input is reduced, lower curve CA

That is, hysteresis effect
**Hysteresis Effect**

- A hysteresis effect occurs when on overloaded driver has some demand removed
  - Ability to process information may be less on downstream side of an overloaded site
  - Before and after analysis methods of design features or traffic control can give erroneous results, because an accident due to poor performance following an overload will not necessarily occur at location giving rise to overload

Source: MUTCD 2009, p. 553 & NCHRP #600, p. 13-3

**Parts of Temporary Traffic Control Zone**
**Work Zone Safety**

- Maximizing the protection of, or reducing risk, danger and injury to, workers and public traffic in work zones.
  - Crashes in work zones result in more injuries and fatalities than the average section of roadway.

*Source: ITE Traffic Engineering Handbook, Ch 15*

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**Temporary Traffic Control Plan**

- **Principal Function of a Traffic Control Plan (TCP)**
  - Provide for the reasonably safe and effective movement of road users through or around the work zone, while protecting workers, incident responders and equipment.
- **Goal of TCP is to route users through/around work zone safely**

**Functional Work Zone Area Concept**

- Understanding and applying the Functional Work Zone Area contributes to safety and operations in the physical work zone area.

*N*OTE: If extended queuing is anticipated, Functional Area may extend beyond initial ROAD WORK AHEAD sign. Mitigations may include Advance Flaggers, additional PCMS, transverse rumble strips, etc.

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**Figure 5. Relation of Functional Work Zone Area to the Physical Work Zone Area at a Temporary Stop**

Adapted from MUTCD 2009, Ch. 6
Work Zone Stopping Sight Distances

Source: 2009 MUTCD, pg. 555

Use Decision Sight Distance in Work Zones

• Recommend using decision sight distance in work zone (DSD) due to:
  – Unfamiliarity
  – Complexity
  – Uniqueness
Decision Sight Distance Design Guidelines

What Does Decision Sight Distance Work For?

- Handles more complexity
  - Compensates for unlimited expectancy
- Decision sight distance PRTs

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>To a stop</td>
<td>3.0 s</td>
<td>6.0 s</td>
<td>9.1 s</td>
</tr>
<tr>
<td>For speed, path or direction change</td>
<td>10.2 s to 11.2 s</td>
<td>12.1 s to 12.9 s</td>
<td>14.0 s to 14.5 s</td>
</tr>
</tbody>
</table>
Signing Errors – *What human factor concept is violated?*

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Work Zone “Positive Guidance”

- **Expectation:** Design Traffic Control Plan (TCP) to meet driver expectations
- **Temporary traffic control emphasizes:**
  - **Primacy:**
    - Placing temporary signs in relation to their importance
    - Avoid presenting information when not essential or applicable
  - **Manage Information:** Avoid too much information at once. Use shorter, successive data bits to convey entire message.
  - **Coding:** Use color, shape and standard messages to present appropriate control and elicit proper driver responses
  - **Redundancy:** Repeat same message in different ways/ mediums (i.e., static signs (text and/or symbols), PCMS)

*Source:* 2009 MUTCD 2009, Chapter 6
Work Zone “Positive Guidance”

• Primacy
  ◆ Advance Warning Area
  ◆ Transition Area
    • Tapers with Channelizing devices; Arrow boards, PCMS
  ◆ Activity Area
    • Warning signs of activity
  ◆ Termination Area
    • Legal end of the work zone – marked by:
    • “END ROAD WORK” sign, last temporary traffic device, or return to original traffic path

Source: MUTCD 2009, Chapter 6, Section 6C

Work Zone “Positive Guidance”

• Manage Information
  – Advanced warning signs
  – Appropriate taper lengths
  – Warning signs within activity areas
  – Providing adequate sight distances

Source: 2009 MUTCD, Chapter 6
Work Zone “Positive Guidance”

- **Coding**
  - Warning: Retroreflective (prismatic), fluorescent orange sheeting
  - Regulatory: Retroreflective, white w/Black non-reflective legend
  - Traffic speed control may be retained

Table 6C-3. Taper Length Criteria for Temporary Traffic Control Zones

<table>
<thead>
<tr>
<th>Type of Taper</th>
<th>Taper Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merging Taper</td>
<td>at least L</td>
</tr>
<tr>
<td>Shifting Taper</td>
<td>at least 0.5 L</td>
</tr>
<tr>
<td>Shoulder Taper</td>
<td>at least 0.33 L</td>
</tr>
<tr>
<td>One-Lane, Two-Way Traffic Taper</td>
<td>50 feet minimum, 100 feet maximum</td>
</tr>
<tr>
<td>Downstream Taper</td>
<td>50 feet minimum, 100 feet maximum</td>
</tr>
</tbody>
</table>

Note: Use Table 6C-4 to calculate L.

Table 6C-4. Formulas for Determining Taper Length

<table>
<thead>
<tr>
<th>Speed (S)</th>
<th>Taper Length (L) in feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 mph or less</td>
<td>( L = \frac{W^2}{60} )</td>
</tr>
<tr>
<td>45 mph or more</td>
<td>( L = WS )</td>
</tr>
</tbody>
</table>

Where: \( L \) = taper length in feet
\( W \) = width of offset in feet
\( S \) = posted speed limit, or off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

* Standard taper lengths from MUTCD

Source: 2009 MUTCD, Chapter 6

Source: 2009 MUTCD, p. 557
Work Zone “Positive Guidance”

- **Redundancy**
  - Redundant information
    - PCMS, “Reminder” signs, Arrow Boards
    - Cover/Remove inappropriate signs and pavement markings
      - Includes existing and temporary signing and markings

*Source: 2009 MUTCD, Chapter 6*

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Design Related Countermeasures

- When shoulders are removed, provide exits and refuge areas at regular intervals.
- Use lane dividers or arrow pavement markers when travel direction changes are made for a lane.

*Source: NCHRP #600, p. 13-3*
Work Zone Sign Legibility

• Contributes to Driver’s ability to see and understand sign messages
• Important Factors
  ♦ Retroreflective Sheeting (“wide angle, prismatic”)
  ♦ Color: Fluorescents (orange, yellow), Red, White, Blue, Green
  ♦ Font and Letter Height: Typically all caps, 3”-8” letter height
  ♦ Sign Locations:
    • Roadside – Post-mounted, Temp. Sign Supports, existing posts
    • Overhead – Existing structures
    • Vehicle-mounted – Pilot Cars, Material Delivery vehicles

Source: NCHRP #600, p. 13-10, ODOT
Motorcyclist & Bicyclist Hazards in Work Zones

- Pavement surface degradation
  - Pavement Quality, Friction surface
- Pavement surface continuity
  - Longitudinal and transverse joints
  - Abrupt edges: Edges of pavement, saw cuts
  - Raise or sunken manholes, clean-outs, inlets, etc.
- Temporary pavement condition
  - Freshly paved or chip sealed
  - Milled or grooved
- Roadway geometrics – Sharp turns, reduced sight distances

Source: Workzonesafety.org
Pavement Surface Quality Degradation Impacts on Motorcyclists & Bicyclists

- Pavement Milling: Longitudinal grooves cause rider instability
- Unpaved/Gravel surfaces: Reduced frictional resistance
- Rough, Broken Pavement: Creates uneven, bumpy sections
- Longitudinal Rumble Strips: Place beyond edge line
- Transverse Rumble Strips: Leave gaps and place warning sign

Source: Workzonesafety.org

Pavement Surface Friction Degradation Impacts on Motorcyclists & Bicyclists

- Loose gravel, sand or soil
  - Rock chips or sand seal debris, material wash, spills
- Liquids on surface
  - Water from overspray, concrete curing, dust control
  - Temporary non-reflective tape in travel path
    - “Black Out” tape to cover conflicting markings
  - Steel plates
    - Very slippery – especially when wet or icy!

Source: Workzonesafety.org
Pavement Surface Continuity Impacts on Motorcyclists & Bicyclists

- **Uneven Lanes**
  - Resulting from milling, asphalt paving, or other work
- **Bridge and Pavement joints**
  - Bridge end panel work, paving lifts, traffic shifts during staging
- **Steel Plates**
  - Smooth, untreated surface often creates problems for riders
- **Manholes and Drainage Features**
  - Elevation differences from milling, new installation and other work

Source: Workzonesafety.org
Degraded Roadway Geometric Impacts on Motorcyclists & Bicyclists

- Traffic lane alignment shifts, or narrowed lane widths
  - Creates rough path with travel lane edge discontinuities
  - Limits maneuverability and “escape routes”
- Elimination of bike lanes
  - Dedicated bike lanes may have to be closed
  - May require detour route or “shared roadway” condition for bicycles

Source: Workzonesafety.org

ODOT Bicycle and Pedestrian Considerations

Attempt to satisfy the following:
1. Match surface levels to existing facilities
2. Keep bicycles and pedestrians outside active work space and away from work equipment
3. Avoid conflicts with traffic, work vehicles, materials and operations
4. Provide adequate advance warning and detour signing for alternate routes

Source: BikePortland.org
5. With existing bicycle facility, maintain 4-ft minimum width, or alternate route
6. Provide a safe and accessible path where sidewalk or ped path exists
7. Close a sidewalk or sidewalk ramp where reasonable alternates exist
Americans with Disabilities Act of 1990 (ADA) ADA requires that pedestrians with physical and/or mental disabilities be accommodated during times of construction.

https://www.workzonesafety.org/training-resources/fhwa_wz_grant/atssa_pedestrian_work_zones/

“Pedestrians should not be led into direct conflicts with mainline traffic moving through or around the worksite.”

[MUTCD Chapter 6D.01]
Benefits of Higher Luminance

• Safety is enhanced with higher luminance
  ◆ On high-speed highways, >50mph
  ◆ Where critical vehicle maneuvers are required
  ◆ Where visual complexity is medium to high
• Improve reflectivity of temporary traffic control devices by using prismatic sheetings
  ◆ Plastic drums, tubular markers, cones, barricades, temporary sign supports (TSS)

Sources: NCHRP #600, p. 13-11; ODOT

Sign Legibility Index

• Can be used to ensure effective designs regardless of:
  ◆ Age or Lighting Conditions
• “Engineering Grade” (Type 3) found to be least effective
• Microprismatic sheetings provided far greater legibility
  ◆ ASTM Types III, IV, VII, VIII and IX most common for temporary
  ◆ Used with fluorescent colors, improves sign conspicuity for:
    ◆ Daytime, nighttime
    ◆ Low-light, dusk, dawn, shadows
    ◆ Inclement weather (rain, fog, snow, etc.)

Source: NCHRP #600, p. 13-10
Background Sign Color

- Yellow and White provide the greatest legibility distance
- Green next most legible
- Orange background provides least
- MUTCD requires black non-reflective legend on orange background for temporary warning signs
  – Use microprismatic orange sheeting

Source: NCHRP #600, p. 13-10

Letter Height

- A maximum legibility index of 40 ft of distance per inch of letter height should be used
- For older drivers, a more conservative value of 33 ft/in

*Height of letter depends on operating speed; see Tutorial 5 (p: 22-29, NCHRP #600)

Source: NCHRP #600, p. 13-10
Sequential Arrows (Arrow Boards)

• An Arrow Board shall have these mode selections:
  A. Flashing arrow, Sequential arrow, or Sequential Chevron mode
  B. Flashing Double Arrow mode
  C. Flashing Caution or Alternating Diamond mode

Source: MUTCD Section 6F.61
Advance Warning Arrow Board Display

- Arrow Board in Mode C shall be used for shoulder work, blocking the shoulder, for roadside work near the shoulder; or, for temporarily closing one lane on two-lane, two-way roadway for short-durations

Source: MUTCD Section 6F.61

Portable Changeable Message Sign (PCMS)

- Portable Changeable Message Sign (PCMS) is a:
  - Large electronic sign
  - Displays programmable, dynamic messages
  - For timely warnings, guidance or notification of traffic conditions
- Can be mounted on a trailer or work vehicle for:
  - Stationary locations – Trailer or Vehicle-mounted
  - Mobile operations – Vehicle-mounted
  - Freeway paving operations – 2-Line PCMS Mounted on Rollers*

* See ODOT Standard Drawing TM880

Source: ODOT Portable Changeable Message Sign Handbook, Sept 2013
PCMS Applications

• A PCMS is a proven effective Traffic Control Device
  ◆ Warning of slowing or stopped traffic in advance of the work zone
  ◆ Alerting Drivers to anticipate traffic queues and delays
  ◆ Displaying adverse weather or environmental conditions (e.g. fog, dust, smoke, etc.)
  ◆ Warning of alignment changes for mainline, ramps, lanes
  ◆ Providing notice of roadway closure schedules and detour routes

Source: ODOT Portable Changeable Message Sign Handbook, Sept 2013

PCMS Applications (Cont.)

• A PCMS can also be effective when:
  ◆ Traffic patterns or lane usage changes (turn lane or climbing/passing lane closures)
  ◆ Supplementing temporary signs and/or pavement markings
  ◆ A temporary/permanent sign or traffic signal has failed
  ◆ Special Events (sporting events, concerts) impact traffic operations
  ◆ Emergency situations occur

Source: ODOT Portable Changeable Message Sign Handbook, Sept 2013
Signing Desirably Should Locate Back of Queue

Impact of Queuing and Delays on Work Zone Traffic Control at High Volume Locations

- Queuing must be taken into account to determine how far effects of work zone are felt
- Traffic controls and signing should warn of stops at location at back of queue
- Delays demonstrate the effect on the traffic stream
Facility Closed by Work Zone

Count of Vehicles

Time

Uniform Arrivals - \( \frac{\text{veh}}{\text{sec}} \)

Facility Closed by Work Zone

Assume a gate is dropped just beyond point A

- Vehicles continue to arrive at A
- Line up, queue up,
- A not seen at B
Facility Closed by Work Zone

- Gate is raised after $t_s$ seconds, i.e., traffic begins to flow
- Traffic output at capacity
- Until queue dissipated

\[ q = \text{input flow} \]
\[ c = \text{capacity} \]
\[ t_s = \text{stopped time} \]
\[ t_q = \text{duration of queuing} \]

Stopped Vehicle Queue from Work Zone Activity

\[ t_s = \text{stopped time} \]
\[ q = \text{input flow} \]
\[ c = \text{capacity} = 0 \]
\[ Q_{\text{MAX}} = \text{maximum queued vehicles} \]
\[ t_q = \text{duration of queuing} \]
Facility Closed by Work Zone

\[ Q_m = \lambda ts \]
\[ N = t_q \]
\[ \text{Delay} = \frac{1}{2} t_s N \]

Capacity Reduced through Work Zone

Capacity is reduced to less than input, \( C_R < q \)

\( t_r = \) period of reduced capacity

Example:
Reduced lanes thru work zone
**Increased Demand Flow Condition thru Capacity Restricted Work Zone**

Demand increases to over-capacity, $q_2 > C$

$$t_i = \text{period of reduced capacity}$$

**Example:**
Work zone with reduced capacity during peak period

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**Increased Demand Flow Analysis**

$q_1 = \text{initial flow, vph}$
$q_2 = \text{peak flow}$
$q_3 = \text{post peak flow}$

$t_i = \text{time of traffic event}$
$t_x = \text{time to dissipate queue}$

$$Q_M = (q_2 - C)t_i$$
$$t_x = Q_M / (C - q_3)$$

$$t_q = t_i + t_x$$
$$N = Ctq$$
Example

A work zone on an arterial has an increase in flow from 1000 vph to 2500 vph for the 1-hr peak hour. Assume the capacity of the open lane is 2000 vph. Determine the size of the queue, $Q_m$, and the duration of queuing, $t_q$.

$$Q_m = (2500 - 2000) \frac{1}{500} = 500 \text{vph}$$

$$t_x = \frac{500 \text{vph}}{(2000 - 1000)} = \frac{1}{2} \text{hr}$$

$$t_q = 1 + \frac{1}{2} = 1 \frac{1}{2} \text{hr}$$

$$N = Ct_q = 2000 (1.5) = 3000 \text{ vph}$$

$$D = \frac{1}{2} Q_m (t_x + t_q) = \frac{1}{2} (500) (1 + \frac{1}{2})$$

$$D = 375 \text{ vph hrs of delay}$$