Effect of short left-turn bay on intersection capacity

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Outline

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- Objective
- Literature review
- Numerical Example
- Deficiencies of the current studies
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Introduction

- At intersections with high left-turn demand in conjunction with high opposing through flow, a protected left-turn signal phase, which can be provided before (leading) or after (lagging) the through movement, is generally used.

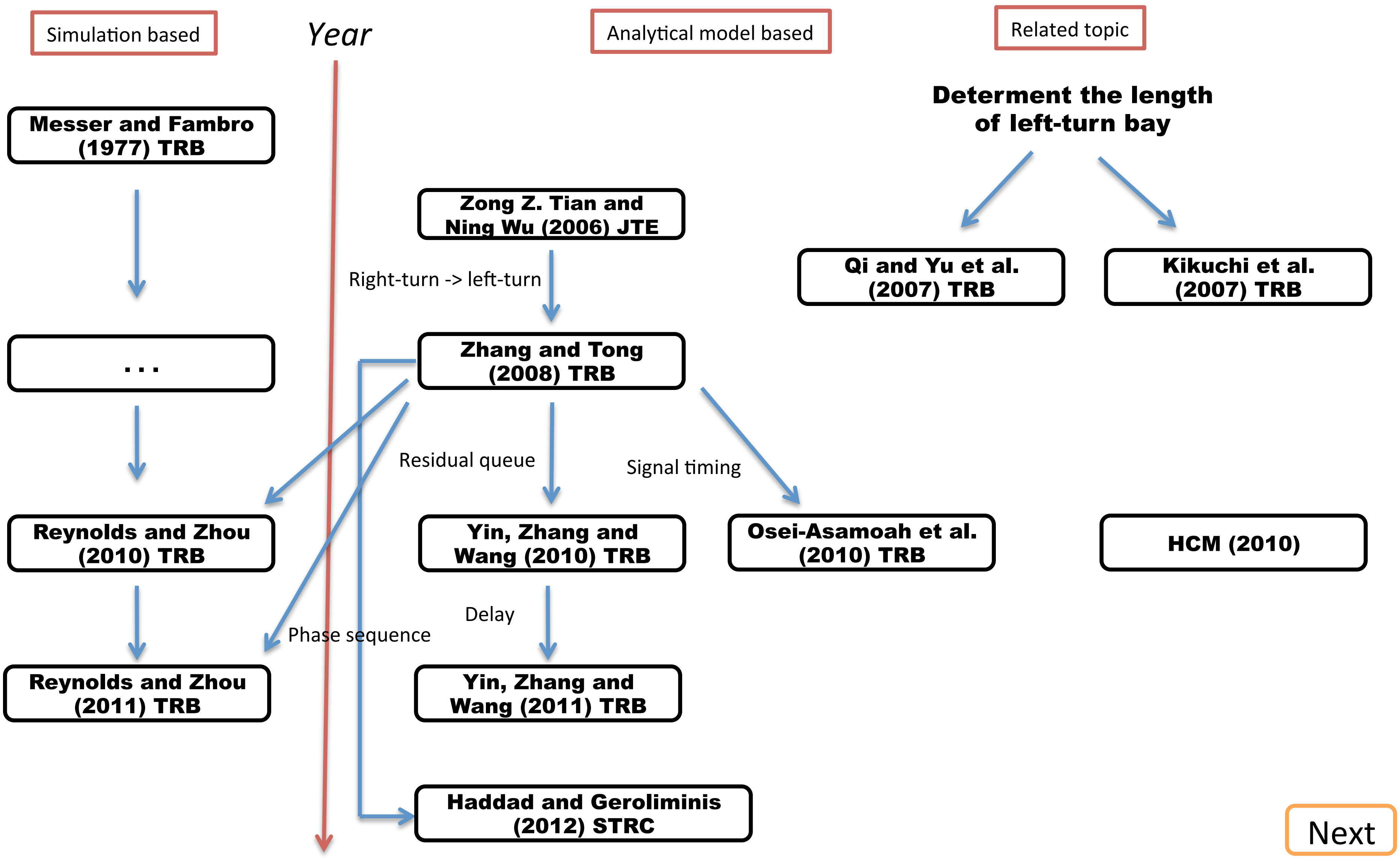
- During the peak hour when there is a high demand of through and left-turn traffic, the length of the left-turn bay may affect the left-turn capacity and sometimes even the adjacent through capacity due to the occurrence of spillback and blockage situation.
  - Blockage: during the green phase of left-turn traffic, the left-turn bay is blocked by the queue of through traffic.
  - Spillback: during the green phase of the through traffic, the adjacent lane next to the left-turn bay is blocked by the queue of left-turn traffic.

Objective

- Objective:
  - Analyze how the **short left-turn bay** will affect the intersection **capacity** under the condition that the left-turn is protected and leading.

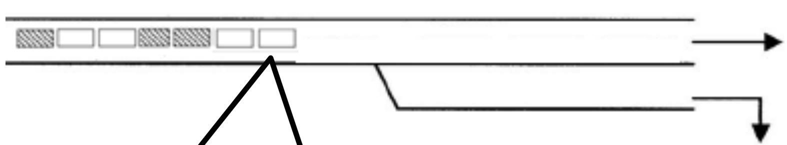
- Input:
  - Arrival rate
  - Geometric information (Number of lanes…)
  - Length of left-turn bay
  - Signal information (Cycle length…)

Literature review

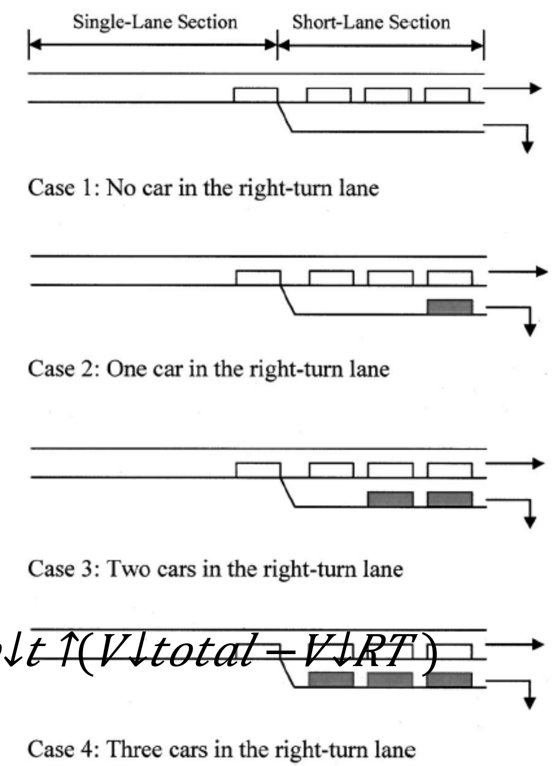


Literature review

- Zong Z. Tian and Ning Wu. **Probabilistic Model for Signalized Intersection Capacity with a Short Right-Turn Lane,** Journal of Transportation Engineering. 2006.



Pt –> through vehicle
(1-pt) --> right turn vehicle



$Pr(x=V_{total})$ ~ Poisson Distribution

$Pr(x=V_{RT})$ ~ $\binom{V_{total}}{V_{RT}}(1-p_t)^{V_{RT}} p_t^{(V_{total}-V_{RT})}$

Back

Literature review

- Zhang and Tong. **Modeling Left-Turn Blockage and Capacity at Signalized Intersection with Short Left-Turn Bay**, TRB, 2008.

Model (Zhang and Tong, TRB 2008)

- Input:

  V_{TH} = m (veh/cycle)

  V_{LT} = n (veh/cycle)

  L (veh)

- Arrival pattern:

  $Pr(x=V_{total}) \sim$ Poisson ($\lambda=m+n$)

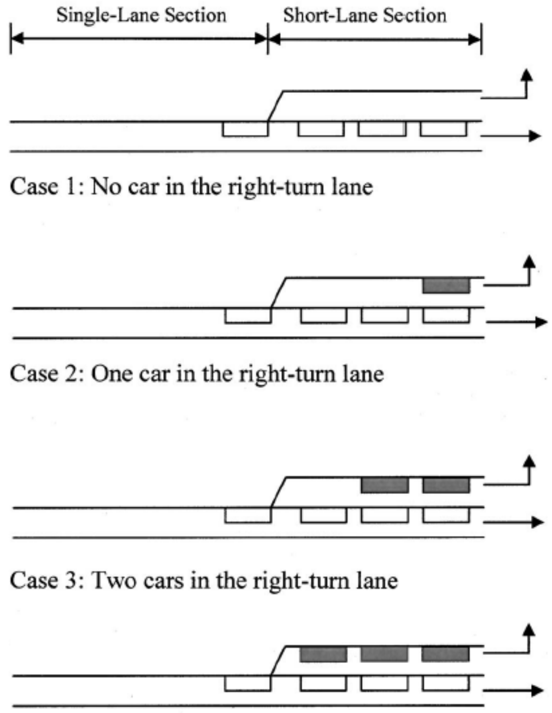
  $Pr(x=V_{LT}) \sim \binom{V_{total}}{V_{LT}}(1-p_t)^{V_{LT}}p_t^{(V_{total}-V_{LT})}$

- Blockage:

  $Pr(Blockage)=Pr(V_{TH} >= L)$ & $Pr(V_{LT} <= L)$

- Spillback:

  $Pr(Spillback)=Pr(V_{TH} <= L)$ & $Pr(V_{LT} >= L)$



Case 1: No car in the right-turn lane

Case 2: One car in the right-turn lane

Case 3: Two cars in the right-turn lane

Case 4: Three cars in the right-turn lane

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Literature review

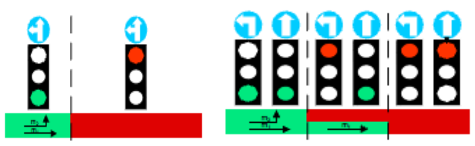
- Analytical model-based

1. Kai Yin, Yunlong Zhang, and Bruce X. Wang. **Analytical Models for Protected plus Permitted Left-Turn Capacity at Signalized Intersection with Heavy Traffic**, TRB, 2010.
   - This paper adjusted Zhang and Tong's paper (2008) by consider the residual queue of the through traffic under heavy traffic situation.

2. Kai Yin, Yunlong Zhang, and Bruce X. Wang. **Modeling Delay During Heavy Traffic for Signalized Intersections with Short Left-Turn Bay**s, TRB, 2011.
   - This paper used the same approach to further analyze the delay by considering blockage and spillback situations.

3. Abigail Osei-Asamoah, Ashish Kulshrestha, et al. **Impact of Left-Turn Spillover on Through Movement Discharge at Signalized Intersections**, TRB, 2010.
   - This paper stated that Zhang and Tong's paper (2008) is the only study identified that explicitly examined the impact of left-turn lane spillover on through movement discharge.
   - This paper adjusted the probability of spillback situation by considering the arrival vehicles during red interval.

4. Jack Haddad, Nikolas Geroliminis. **Capacity of arterials with left-turn queue spillbacks**, STRC, 2012.
   - This paper considered two different signal phase sequences.



(a) Two phases (b) Three phases

Back

Literature review

- Simulation-based

1. William L. Reynolds, Xuesong Zhou, et al. **Estimating Sustained Service Rates at Signalized Intersections with Short Left-Turn Pockets**, TRB, 2010.

2. William L. Reynolds et al. **Turn Pocket Blockage and Spillback Models**, TRB, 2011
   - Using cell transmission model with the assumption that the arrival pattern is uniformed.

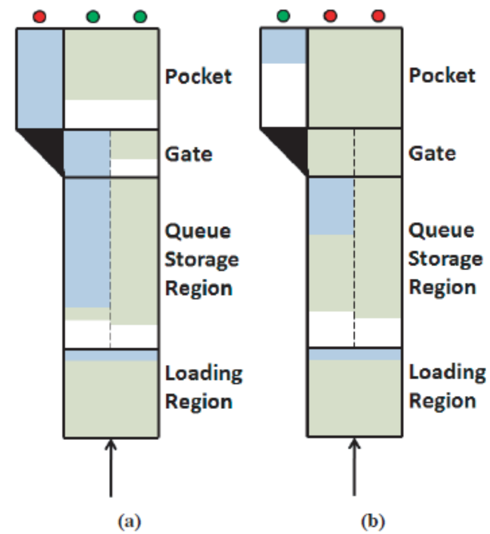


FIGURE 1 Cell-based macroscopic operation: (*a*) spillback and (*b*) blockage.

- Simulation-based method can consider more details and the result may be closer to reality, however it's hard to be applied in general and it needs lots of energy and time.

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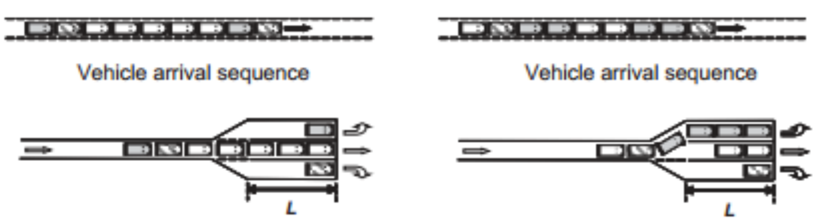
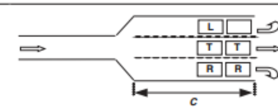
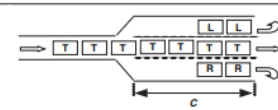
Literature review

- Determent the length of left-turn bay
  - Yi Qi, Lei Yu, Mehdi Azimi, and Lei Guo. **Determination of storage lengths of left turn lanes at signalized intersections**. TRB, 2007.
    - Estimate the queue length under 95% confident interval based on arrival pattern, and make the length of left-turn bay larger than it to avoid blockage situation.
  - Shinya Kikuchi, Nopadon Kronprasert, and Masanobu Kii. **Lengths of Turn Lanes on Intersection Approaches.** TRB, 2007.
    - Define some acceptable conditions (threshold probability) and calculate the suitable bay length that satisfies the thresholds.



(a) (b)

Case	Pattern of Arrivals	Probability
1	$j \le C$, $i \le C$, $k \le C$ 	$\sum_{i=0}^{C}\sum_{j=0}^{C}\sum_{k=0}^{C}\frac{(\lambda_T)^i e^{-\lambda_T}}{i!}\frac{(\lambda_L)^j e^{-\lambda_L}}{j!}\frac{(\lambda_R)^k e^{-\lambda_R}}{k!}$
2	$j \le C$, $i > C$, $k \le C$ 	$\sum_{i=C+1}^{\infty}\sum_{j=0}^{C}\sum_{k=0}^{C}\frac{(\lambda_T)^i e^{-\lambda_T}}{i!}\frac{(\lambda_L)^j e^{-\lambda_L}}{j!}\frac{(\lambda_R)^k e^{-\lambda_R}}{k!}\frac{\begin{pmatrix} C+j+k \\ C\ \ j\ \ k \end{pmatrix}}{\begin{pmatrix} i+j+k \\ i\ \ j\ \ k \end{pmatrix}}$

Back

Literature review

- HCM 2010
  - Capacity of unsignalized intersections with left-turn bays

$$p_{ov} = \left(\frac{v_{lt}}{c_l}\right)^{N_{qx,lt}+1}$$

with

$$N_{qx,lt} = \frac{N_{lt}\ L_{a,lt}}{L_h}$$

where

p_{ov} = probability of left-turn bay overflow (decimal),

$N_{qx,lt}$ = maximum queue storage for the left-turn movement (veh),

N_{lt} = number of lanes in the left-turn bay (ln),

$L_{a,lt}$ = available queue storage distance for the left-turn movement (ft/ln), and

L_h = average vehicle spacing in the stationary queue (see Equation 30-10) (ft/veh).

c_l = capacity of a left-turn movement with permitted left-turn operation (veh/h);

v_{lt} = left-turn demand flow rate (veh/h).

Literature review

- HCM 2010
  - Capacity of signalized intersections with left-turn bays
    - No recommended model, only some simulation results under some assumed scenarios.
    - For case-specific applications, parameters that could influence the evaluation of bay overflow include the following:
      - Number of lanes for each movement,
      - Demand volumes for each movement,
      - Impedance of left-turning vehicles by oncoming traffic during permitted periods,
      - Signal timing plan (cycle length and phase times),
      - Factors that affect the number of left-turn sneakers for left-turn movements that have permitted operation, and
      - Other factors that influence the saturation flow rates.

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Numerical Example (Method from Zhang and Tong 2008)

- Input:
  - -Left-turn traffic arrival rate: λ_{LT}=400veh/h;
  - -Through traffic arrival rate: λ_{TH}=800veh/h;
  - -Number of through lanes: nl=2;
  - -Length of left-turn bay: N=6veh;
  - -Cycle length: C=90s;
  - -Through traffic green time: g_{TH}=27s;
  - -Left-turn traffic green time: g_{LT}=27s;
  - -Saturation flow rate: s=2000veh/h;
  - -Phase sequence: left-turn leading.

Numerical Example (Method from Zhang and Tong 2008)

- **Step 1:** Calculate the blockage probability:
  - When number of arriving vehicle per cycle is less than 2N:

$$PBlockage(V<2N)=\sum_{V=N}^{V=2N-1}\sum_{vLT=0}^{vLT=V-N} P(x=V)*\binom{V}{vLT}\, pt^{(V-vLT)}\,(1-pt)^{vLT}$$

Where,

V is the total arriving vehicle number;

v_{LT} is the number of left-turn vehicles that can enter the left-turn bay before blockage;

P(x=V) is the probability that arriving vehicle number equals to V under Poisson distribution with $\lambda=\lambda_{LT}+\lambda_{TH}$, which can be calculated as: $P(x=V)=\lambda^{V}*e^{-\lambda}/V!$;

p_t is the percentage of through traffic, which equals to $p_t = \lambda_{TH}/(\lambda_{LT}+\lambda_{TH})$;

  - When number of arriving vehicle per cycle is less than 2N:

$$PBlockage(V\geq 2N)=\sum_{V=2N}^{V=VMax}\sum_{vLT=0}^{vLT=N-1} P(x=V)*\binom{V}{vLT}\, pt^{(V-vLT)}\,(1-pt)^{vLT}$$

Where,

Numerical Example

- **Step 1:** Calculate the blockage probability:
  - Calculate the total probability of blockage:

$$PBlockage = PBlockage(V < 2N) + PBlockage(V \geq 2N)$$

  - In this case, $P_{Blockage}$=49.7%.

Numerical Example

- **Step 2:** Calculate the expected number of left-turn vehicles that can can arrive before blockage situation :
  - When number of arriving vehicle per cycle is less than 2N:

$$E_{vLT}(V<2N) = \sum_{V=N}^{V=2N-1} \sum_{v_{LT}=0}^{v_{LT}=V-N} v_{LT} * P(x=V) * \binom{V}{v_{LT}} p_t^{(V-v_{LT})} (1-p_t)^{v_{LT}}$$

Where,

V is the total arriving vehicle number;

v_{LT} is the number of left-turn vehicles that can arrive before blockage situation;

$P(x=V)$ is the probability that arriving vehicle number equals to V under Poisson distribution with $\lambda=\lambda_{LT}+\lambda_{TH}$, which can be calculated as: $P(x=V)=\lambda^V * e^{-\lambda} / V!$;

p_t is the percentage of through traffic, which equals to $p_t = \lambda_{TH}/(\lambda_{LT}+\lambda_{TH})$;

  - When number of arriving vehicle per cycle is less than 2N:

$$E_{vLT}(V\geq 2N) = \sum_{V=2N}^{V=V_{Max}} \sum_{v_{LT}=0}^{v_{LT}=N-1} v_{LT} * P(x=V) * \binom{V}{v_{LT}} p_t^{(V-v_{LT})} (1-p_t)^{v_{LT}}$$

Where,

V_{Max} is the maximum number of vehicle that possibly can arrival in one cycle;

Numerical Example

- **Step 2:** Calculate the expected number of left-turn vehicles that can arrive before blockage situation:
  - Calculate the total expected number:

$$E(vLT)=EvLT(V<2N)+EvLT(V\geq 2N)$$

  - In this case, $E(v_{LT})=2.06$.

- **Step 3:** Calculate the left-turn capacity under the given condition:
  - Left-turn capacity:

$$CLT=E(vLT)+(1-PBlockage)*\mathrm{s}*\mathrm{gLT}/\mathrm{C}$$

  - In this case, C_{LT}=9.59 (veh/cycle) or 1280 (veh/h)

Numerical Example

- **Step 4:** Calculate the spillback probability:
  - When number of arriving vehicle per cycle is less than 2N:

$$P_{Spillback}(V\le 2N)=\sum_{V=N+1}^{V=2N}\sum_{v_{TH}=0}^{v_{TH}=V-N-1} P(x=V)*\binom{V}{v_{TH}}\, p_t^{v_{TH}}(1-p_t)^{(V-v_{TH})}$$

Where,

V is the total arriving vehicle number;

v_{TH} is the number of left-turn vehicles that pass adjacent through lane before spillback;

$P(x=V)$ is the probability that arriving vehicle number equals to V under Poisson distribution with $\lambda=\lambda_{LT}+\lambda_{TH}$, which can be calculated as: $P(x=V)=\lambda^{V}*e^{-\lambda}/V!$;

p_t is the percentage of through traffic, which equals to $p_t=\lambda_{TH}/(\lambda_{LT}+\lambda_{TH})$;

  - When number of arriving vehicle per cycle is less than 2N:

$$P_{Spillback}(V>2N)=\sum_{V=2N+1}^{V=V_{Max}}\sum_{v_{TH}=0}^{v_{TH}=N-1} P(x=V)*\binom{V}{v_{LT}}\, p_t^{v_{TH}}(1-p_t)^{(V-v_{TH})}$$

Where,

Numerical Example

- **Step 4:** Calculate the blockage probability:
  - Calculate the total probability of blockage:

$$PSpillback = PSpillback(V \leq 2N) + PSpillback(V > 2N)$$

  - In this case, $P_{Blockage}$=27.5%.

- **Step 5:** Calculate the expected number of through vehicles that can arrive before spillback in each cycle:
  - Using the same method as step 3,

$$E(vTH) = EvLH(V \leq 2N) + EvLH(V > 2N)$$

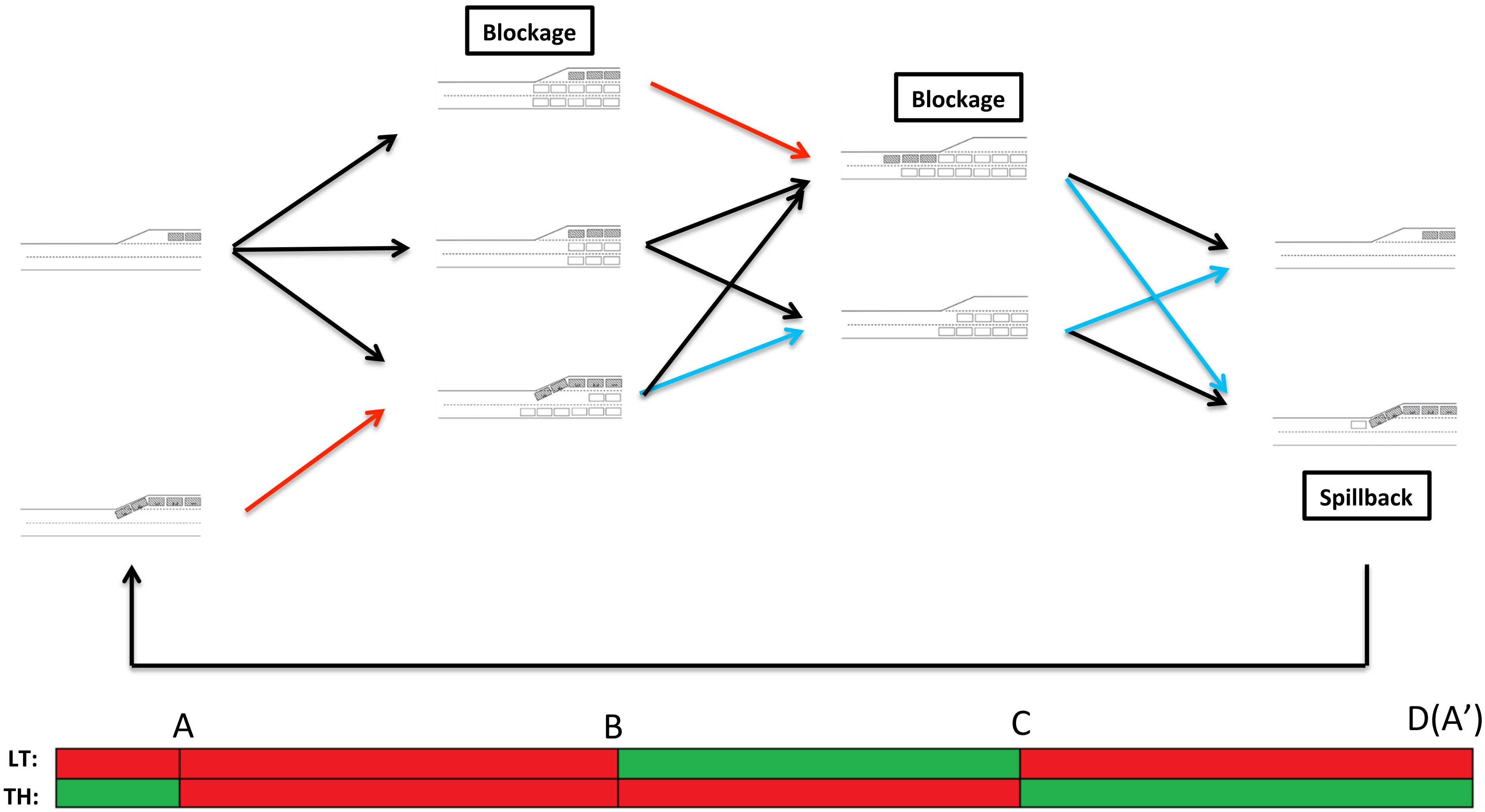
  - So in this case, $E(v_{TH})$=0.95.

- **Step 6:** Calculate the through capacity under the given condition:
  - Through capacity:

$$CTH = (E(vTH) + P\mathrm{Spillback} * \mathrm{s} * (\mathrm{nl} - 1) * \mathrm{gTH}/\mathrm{C}) + (1 - P\mathrm{Spillback}) * \mathrm{s} * \mathrm{nl} * \mathrm{gTH}/\mathrm{C}$$

Deficiencies of the current studies

- Process of a cycle:



Deficiencies of the current studies

- Deficiency 1:
  - The model has not considered that red phase for left-turn traffic starts earlier than the red phase for through traffic.

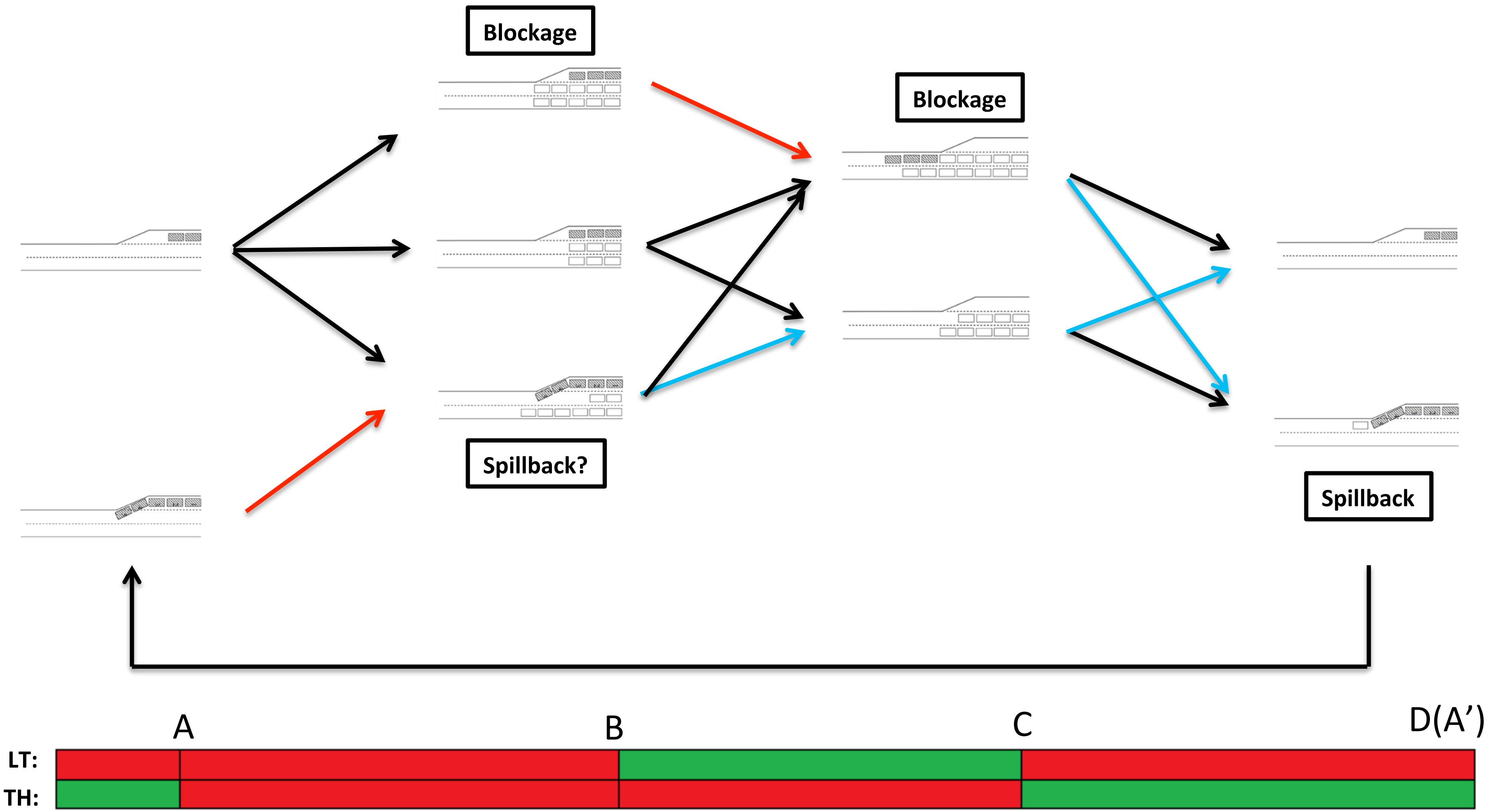
$$Pr(Blockage)=Pr(X_{TH}>=N+2)*Pr(X_{LT}<=N+2)$$

  - The initial queue for the left-turn traffic has been ignored.

$$Pr(Blockage)=Pr(X_{TH}>=N+2)*Pr(X_{LT}<=N+2-q_{LT})$$

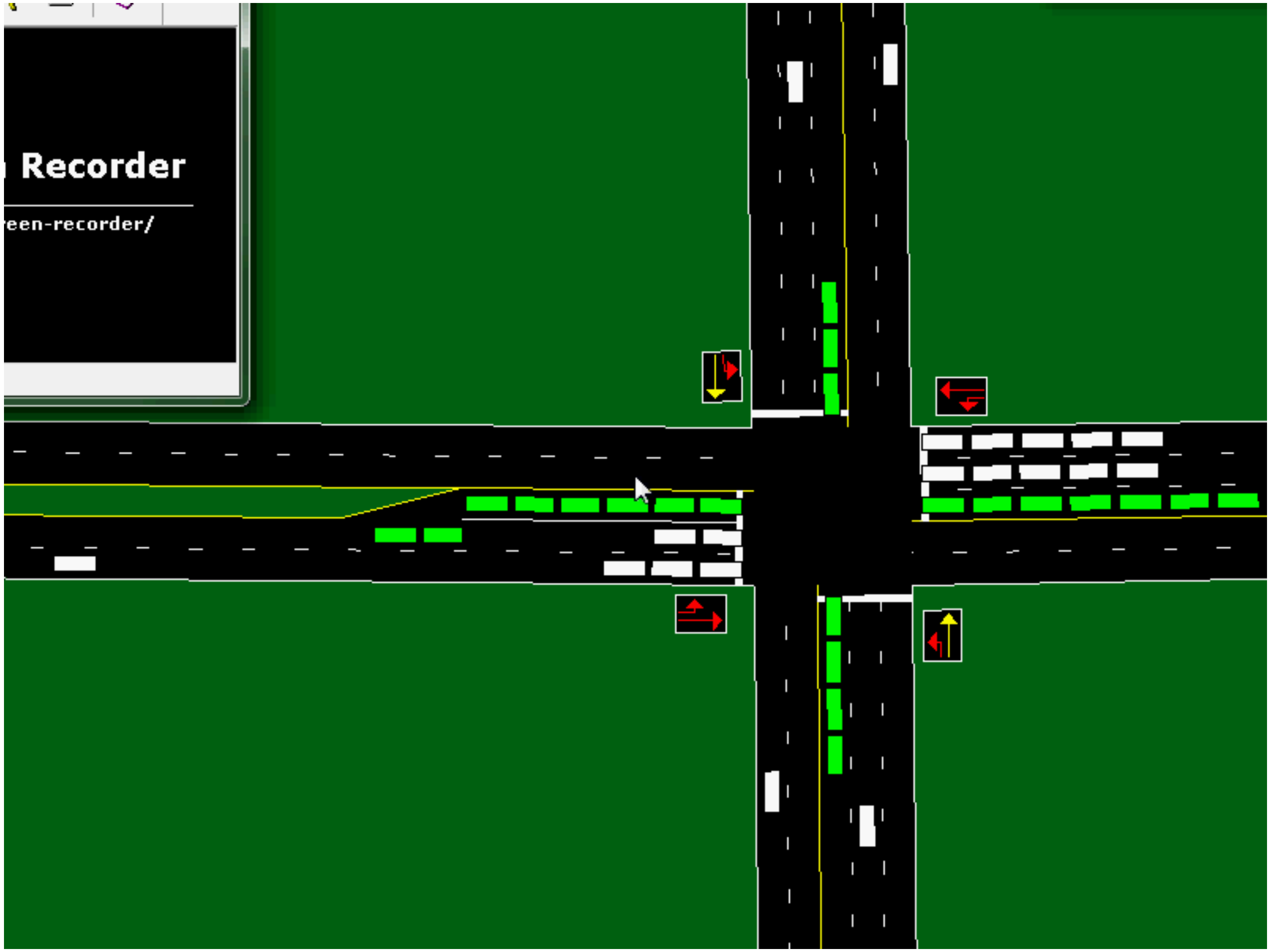
Deficiencies of the current studies

- Process of a cycle:



Deficiencies of the current studies

Video:



Deficiencies of the current studies

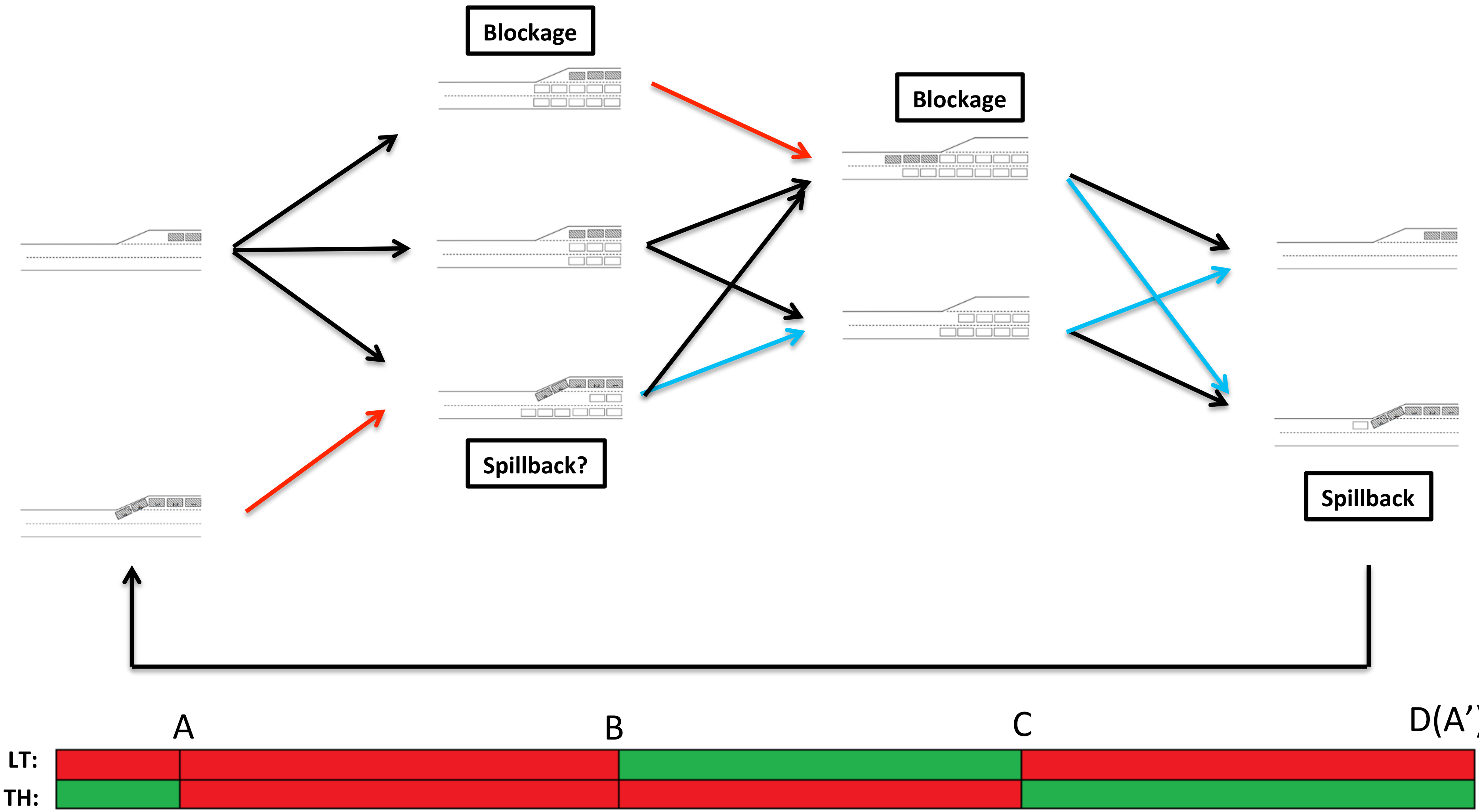
- Deficiency 2:
  - The current model cannot well reflect the real spillback cases.

$$Pr(Spillback)=Pr(X_{TH}<=N+2)*Pr(X_{LT}>=N+2)$$

  - The probability of spillback situation may be overestimated.

Deficiencies of the current studies

- Process of a cycle:



Further analysis

- Idea

Point A:

Existing queue (q_{LT})

Point A → Point C:

Probability of blockage (Pr_{block})

Expected # of LT vehicles that pass the intersection ($V_{capacity}$)

Expected # of LT vehicles that do not pass (V_{nopass})

Point C → Point A':

Probability of spillback under all different cases (Pr_{spill})

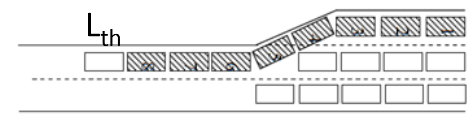
New expected existing queue for next cycle (q_{LT}')

Further analysis

- Input:
  - Left-turn traffic arrival rate: a_{LT} (veh/h);
  - Total through traffic arrival rate: a_{TH} (veh/h);
  - Cycle length: C (s);
  - Green time for through traffic: g_{TH} (s);
  - Green time for left-turn traffic: g_{LT} (s);
  - Bay length: L (veh);
  - Saturation flow rate: s (veh/h);
  - Initial existing left-turn queue at A: q_{LT}^{A}

Further analysis

- Notation:
  - i is the number of through vehicles arriving during AC;
  - j is the number of left-turn vehicles arriving during AC;



  - k is the number of left-turn vehicles arriving the intersection before the L^{th} through arriving vehicles;
  - C_{ij} is the expected number of left-turn vehicles that can pass the intersection by the end of green interval of left-turn phase, under the given i and j;
  - R_{ij} is the expected number of left-turn vehicles that stay in queue at the end of green interval of left-turn phase, under the given i and j;
  - s_{TH} is the maximum number of vehicles that can pass the intersection during the green interval for through traffic in one cycle;
  - s_{LT} is the maximum number of vehicles that can pass the intersection during the green interval for left-turn traffic in one cycle;
  - C_{TH} and C_{LT} are the capacity for through and left-turn traffic.

Further analysis

- Assumptions:
  1. Arrival patterns of through and left-turn traffic follow two stable and independent Poisson distributions respectively;
  2. Traffic demand is under saturation condition;
  3. All left-turn vehicles use the left-side through lane before reaching the left-turn bay;
  4. Signal timing is fixed.

Further analysis

- Starting Point: A
  - Assume q_{LT}^{A} is given, and $q_{TH}^{A}=0$

- Point A -> Point C (Blockage condition)

Case 1

- **When i<L**

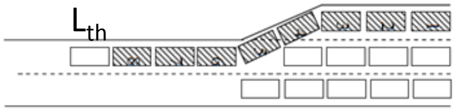
(Through arriving vehicles is less than the bay length, no blockage)

- $Pr_{block}=0\%$
- and $C_{ij}=s_{LT}$;
- and $R_{ij}=Max\{j+q_{LT}^{A}-s_{LT},0\}$

Further analysis

- Point A -> Point C

Case 2



- **When i $\geq$ L and j< $s_{LT} - q$**

(All left-turn vehicles arrive before L^{th} through vehicle will be discharged during the green interval BC, and blockage always happens)

- Pr_{block}=100%
- P(k)=$C_{L+k-1}^{k} C_{i+j-k-L}^{i-L} / C_{i+j}^{i}$ (The probability that k left-turn vehicles arrive before L^{th} through vehicle)
- E(k)=$\sum_{k=0}^{k=j} k*P(k)$ (The expected value of k under blockage condition)
- and $C_{ij} = E(k) + q_{LT}^{A}$
- and $R_{ij} = j - E(k)$

Further analysis

- Point A -> Point C

Case 3

- **When $i \geq L$ and $j \geq s_{LT} - q_{LT}^{A}$**

(When the number of left-turn vehicles arrive before Lth through vehicle exceed the maximum discharging vehicle number, then no blockage)

Case 3.A (Blockage)

- **When $k < s_{LT} - q_{LT}^{A}$**
  - Pr_{block}=100%
  - P(k)=$C_{L+k-1}^{k} C_{i+j-k-L}^{i-L} / C_{i+j}^{i}$ (The probability that k left-turn vehicles arrive before Lth through vehicle)
  - $E_{block}(k)=\sum_{k=0}^{(s_{LT}-q_{LT}^{A})-1} k * P(k)$ (The expected value of k under blockage condition)

Further analysis

- Point A -> Point C

Case 3

- **When i $\geq$ L and j $\geq s_{LT} - q_{LT}^{A}$**

(When the number of left-turn vehicles arrive before Lth through vehicle exceed the maximum discharging vehicle number, then no blockage)

Case 3.B (No Blockage)

- **When k$\geq s_{LT} - q_{LT}^{A}$**
  - Pr_{block}=0%
  - P(k)= $C_{L+k-1}^{k} C_{i+j-k-L}^{i-L} / C_{i+j}^{i}$ (The probability that k left-turn vehicles arrive before Lth through vehicle)
  - $E_{Noblock}$(k)= $\sum_{k=(s_{LT} - q_{LT}^{A})}^{j} (s_{LT} - q_{LT}^{A}) * P(k)$ (The expected value of k under no blockage condition)

Further analysis

- Point A -> Point C

Case 3

- So the final $E(k)=E_{block}(k)+E_{Noblock}(k)$
- and $C_{ij}=E(k)+q_{LT}^{A}$
- and $R_{ij}=j-E(k)$

Here all cases during AC are discussed.

- So the expected capacity of left-turn traffic can be calculated:

$$C_{LT}=\sum_{i}\sum_{j}C_{ij}*P(i)*P(j)$$

  - Where P(i) ~ Poisson (λ is unknown)

    P(j) ~ Poisson ($\lambda=a_{LT}*r_{AC}$)

Further analysis

- Point C -> Point D (Spillback condition)
  - Since the Rij is obtained at Point C, so the spillback probability can be calculated as:

Case 1:

When $R_{ij} \geq L+1$

– P_{ij} (spillback)=1 (Already spillback)

Case 2:

When $R_{ij} < L+1$

– P_{ij} (spillback)=P(x>=L+1-R_{ij})

- Where P(x) ~ Poisson (λ=$a_{LT} * r_{CD}$)

Further analysis

- So the final probability of spillback can be calculated:

$$P(\text{spillback}) = \sum_{i} \sum_{j} P_{ij}(\text{spillback}) * P(i) * P(j)$$

Where P(i) ~ Poisson ($\lambda = unknown$)

P(j) ~ Poisson ($\lambda = a_{LT} * r_{AC}$)

- So the final capacity of through traffic can be calculated:

$$C_{TH} = (1 - P(\text{spillback})) * s_{TH} * nl + P(\text{spillback}) * s_{TH} * (nl - 1)$$

Where nl is the number of through lanes

Further analysis

- Problem 1:
  - Arrival rate of through traffic in adjacent through lane is unknown.

$$C_{LT} = \sum_i \sum_j C_{ij} * P(i) * P(j)$$

  - Where P(i) ~ Poisson (λ is **unknown**)

    P(j) ~ Poisson ($\lambda = a_{LT} * r_{AC}$)

- Method:
  - Build a model to estimate the arrival rate of through traffic in adjacent through lane, based on the left-turn volume, total through volume and length of left-turn bay.

Further analysis

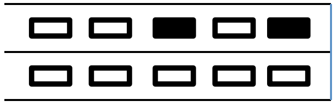
- Input:
  - Left-turn arrival rate: V_{LT} (veh/h)
  - Total through arrival rate: V_{TH} (veh/h)
  - Left-turn bay length: L (veh)

- Assumption:
  - All left-turn traffic use the adjacent though lane before entering the left-turn bay.

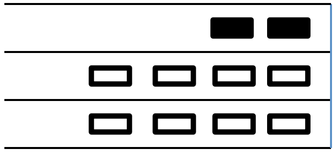
- Output:
  - Arrival rate of through traffic at adjacent through lane: V_1 (veh/h)

Further analysis

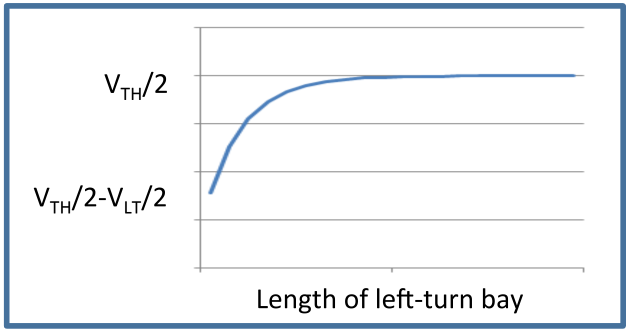
- Method:
  - Case 1: L=0 (No left-turn bay)
    - All traffic evenly distribute between two through lanes:
    - $V_1 + V_{LT} = V_{TH} - V_1$ -> $V_1 = V_{TH}/2 - V_{LT}/2$



  - Case 2: L-> ∞ (Exclusive left-turn lane)
    - All through traffic evenly distribute:
    - $V_1 = V_{TH}/2$



  - Normal case: With the increase of L, the V_1 increases



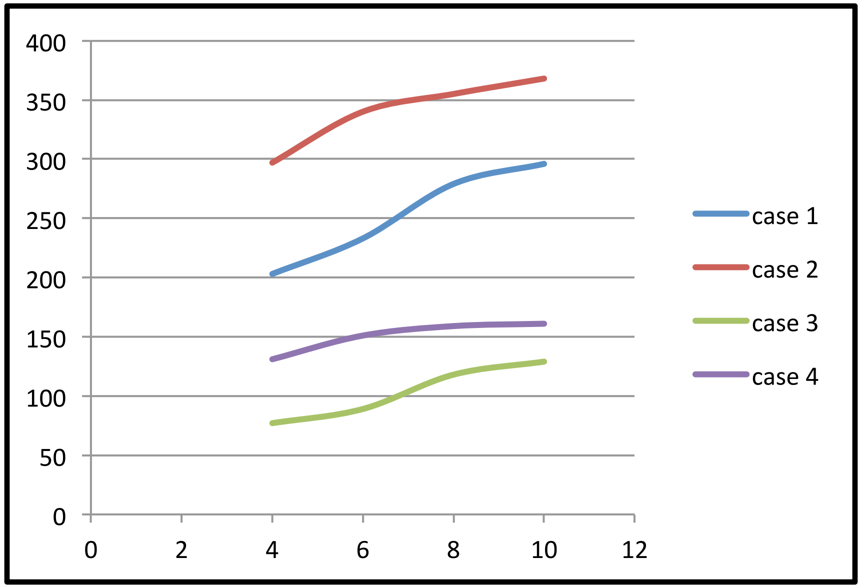
Assumed relation:

$$V_1 = V_{TH}/2 - e^{-\boldsymbol{a}L} * V_{LT}/2$$

Further analysis

- Use simulation results to obtain the parameter a.
  - Scenarios:

	LT vph	TH vph	Bay length	# veh in Lane 1	Parameter a
Case 1	400	800	4	203	0.00378
	400	800	6	233	0.03005
	400	800	8	279	0.06282
	400	800	10	296	0.06539
Case 2	200	800	4	297	-0.00739
	200	800	6	340	0.08514
	200	800	8	355	0.09981
	200	800	10	368	0.11394
Case 3	400	400	4	77	0.12153
	400	400	6	89	0.09813
	400	400	8	118	0.11145
	400	400	10	129	0.10356
Case 4	200	400	4	131	0.09277
	200	400	6	151	0.11889
	200	400	8	159	0.11145
	200	400	10	161	0.09416
				AVG	**0.08159**



Model to estimate the V_1 :

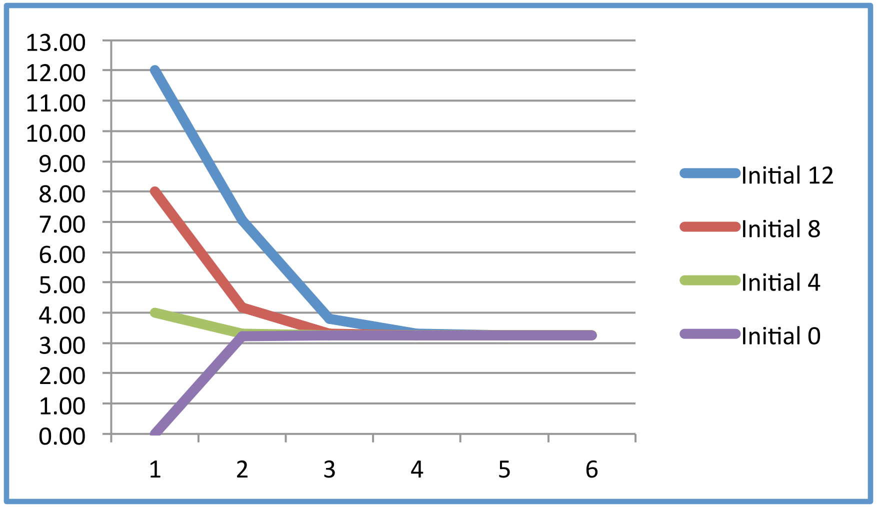
$$V_1 = V_{TH}/2 - e^{-0.08L} * V_{LT}/2$$

Further analysis

- Problem 2:
  - Initial existing queue -> not known
- Method:
  - Given any reasonable queue at first and after several iterations, see if the queue will become stable.

Further analysis

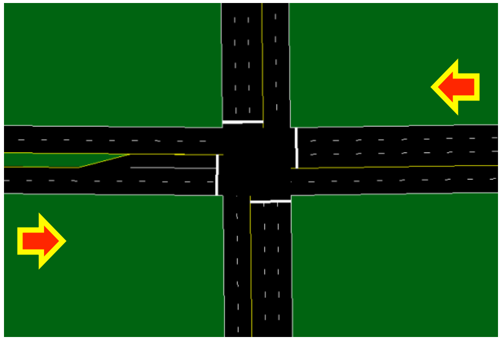
- Result
  - left-turn traffic arrival rate (veh/hour): 400vph
  - through traffic arrival rate (veh/hour): 800vph
  - the saturation flow rate (veh/hour) : 2000vph
  - number of through lanes: 2
  - cycle length AD: 90s
  - through traffic green interval CD: 27s
  - left-turn traffic green interval BC: 27s
  - the length of left-turn lane : 6 veh
  - Note: if the input changes, the output shows the same pattern as above.



- Conclusion:
  - Result shows that no matter the starting existing queue is, after several iteration, the left-turn queue and Point D becomes stable.
  - When the existing queue becomes stable, the resulting left-turn and through capacity should be regarded as the capacity for the target approach.

Model validation

- Scenarios
  - Intersection geometry:
    - Target approach: Two through lanes, one left-turn bay.
    - Other approaches: Two through lanes, one left-turn lane.
    - Length of left-turn bay: 4veh, 6veh, 8veh, 10veh.



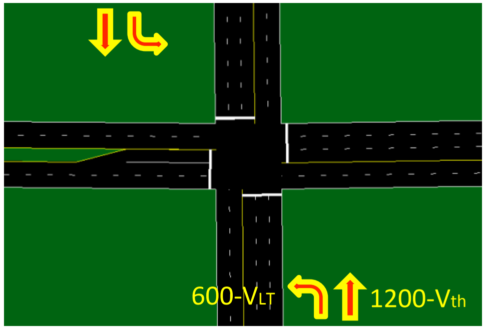
  - Traffic volume:
    - Target approach (W->E):

      Through traffic: 500vph, 600vph, 700vph, 800vph.

      Left-turn traffic: 200vph, 300vph.

      Saturation flow rate: 2000vph
    - Opposite approach (E->W): The same with target approach.
    - Other approaches (N->S & S->N): Keep the same with each other and change with W-E approaches in order to keep the CLV(1800vph) and cycle length(90s) constant.
      - Reason: Input of the model is the arrival vehicles per cycle;

        When one variables (through or left-turn volume) stay the same, the green time stay the same.



  - Signal plan:
    - Cycle length: 90s (If using webster's equation: 75s)
    - Green splits: Using Synchro to obtain the optimal plans.
  - Simulation:
    - Using CORSIM to run for 3600 time steps.
    - Every scenario uses three different random seeds to observe the number of blockage and spillback situation in order to get the average probability.

Scenarios

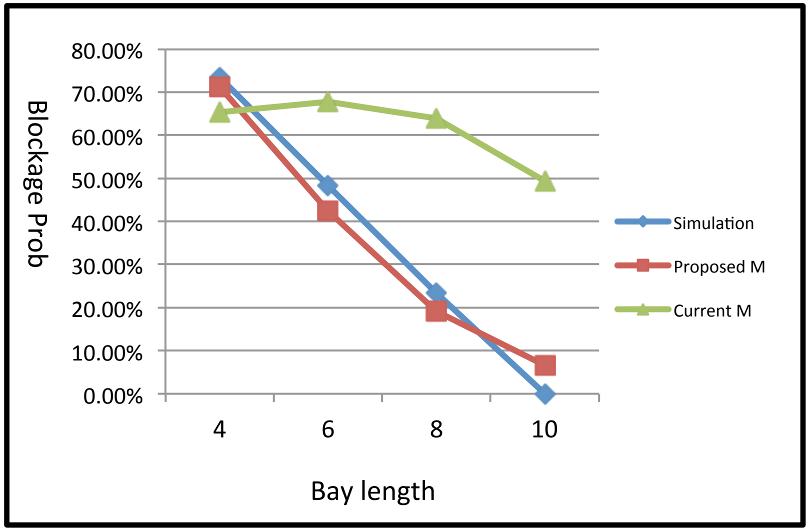
Scenarios	LT vph	TH vph	Bay length	# of TH lanes	CYCLE	TH GREEN	LT GREEN
Case 1	300	800	4	2	90	28	21
	300	800	6	2	90	28	21
	300	800	8	2	90	28	21
	300	800	10	2	90	28	21
Case 2	300	700	4	2	90	24	21
	300	700	6	2	90	24	21
	300	700	8	2	90	24	21
	300	700	10	2	90	24	21
Case 3	300	600	4	2	90	24	22
	300	600	6	2	90	24	22
	300	600	8	2	90	24	22
	300	600	10	2	90	24	22
Case 4	300	500	4	2	90	21	22
	300	500	6	2	90	21	22
	300	500	8	2	90	21	22
	300	500	10	2	90	21	22
Case 5	200	800	4	2	90	27	16
	200	800	6	2	90	27	16
	200	800	8	2	90	27	16
	200	800	10	2	90	27	16
Case 6	200	700	4	2	90	26	16
	200	700	6	2	90	26	16
	200	700	8	2	90	26	16
	200	700	10	2	90	26	16
Case 7	200	600	4	2	90	24	16
	200	600	6	2	90	24	16
	200	600	8	2	90	24	16
	200	600	10	2	90	24	16
Case 8	200	500	4	2	90	22	16
	200	500	6	2	90	22	16
	200	500	8	2	90	22	16
	200	500	10	2	90	22	16

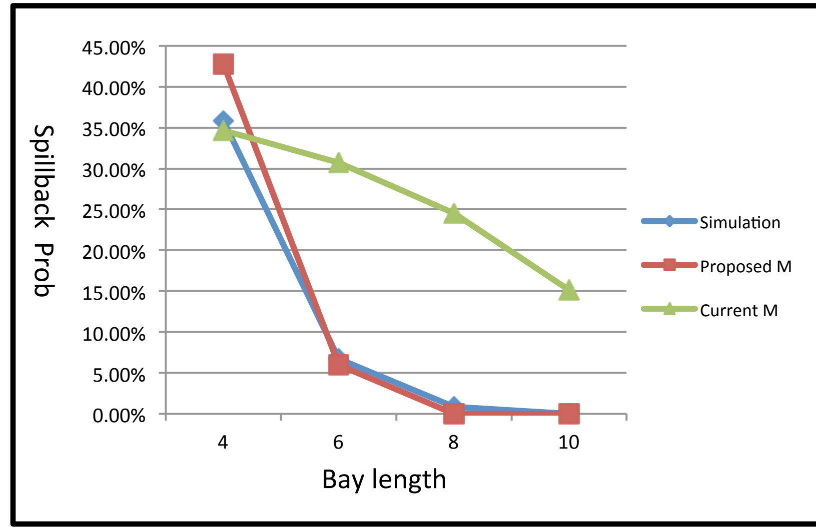
Results

LT vph	TH vph	Bay length	# of TH lanes	CYCLE	TH GREEN	LT GREEN	Blocakge Prob			Spillback Prob		
							Simulation	Proposed Model	Current model	Simulation	Proposed Model	Current model
300	800	4	2	90	28	21	73.33%	71.20%	65.27%	35.83%	42.70%	34.67%
300	800	6	2	90	28	21	48.33%	42.40%	67.69%	6.67%	5.97%	30.69%
300	800	8	2	90	28	21	23.33%	19.10%	63.92%	0.83%	0.00%	24.53%
300	800	10	2	90	28	21	0.00%	6.53%	49.36%	0.00%	0.00%	15.09%
300	700	4	2	90	24	21	55.00%	62.85%	58.28%	25.83%	32.01%	41.57%
300	700	6	2	90	24	21	35.83%	32.83%	58.51%	1.67%	3.20%	38.31%
300	700	8	2	90	24	21	10.83%	12.69%	51.07%	0.00%	0.02%	30.36%
300	700	10	2	90	24	21	0.00%	3.78%	34.14%	0.00%	0.00%	17.70%
300	600	4	2	90	24	22	48.33%	45.80%	49.83%	11.67%	21.74%	49.83%
300	600	6	2	90	24	22	30.83%	18.06%	47.09%	0.83%	0.19%	47.09%
300	600	8	2	90	24	22	7.50%	5.36%	36.24%	0.00%	0.00%	36.24%
300	600	10	2	90	24	22	0.00%	0.12%	19.86%	0.00%	0.00%	19.86%
300	500	4	2	90	21	22	32.50%	28.12%	39.80%	8.33%	12.50%	59.43%
300	500	6	2	90	21	22	14.17%	8.42%	33.78%	0.00%	0.07%	56.41%
300	500	8	2	90	21	22	0.83%	1.80%	21.43%	0.00%	0.00%	41.38%
300	500	10	2	90	21	22	0.00%	0.00%	8.98%	0.00%	0.00%	21.32%
200	800	4	2	90	27	16	67.50%	81.31%	82.47%	13.33%	19.58%	17.26%
200	800	6	2	90	27	16	54.17%	52.90%	84.55%	0.83%	1.41%	11.32%
200	800	8	2	90	27	16	20.00%	26.38%	75.05%	0.00%	0.00%	5.87%
200	800	10	2	90	27	16	1.67%	9.81%	53.66%	0.00%	0.00%	2.01%
200	700	4	2	90	26	16	57.50%	71.39%	77.24%	10.83%	15.37%	22.09%
200	700	6	2	90	26	16	39.17%	40.17%	76.69%	1.67%	0.72%	15.20%
200	700	8	2	90	26	16	15.83%	16.29%	61.69%	0.00%	0.00%	7.64%
200	700	10	2	90	26	16	0.00%	4.90%	37.52%	0.00%	0.00%	2.42%
200	600	4	2	90	24	16	41.67%	58.63%	70.01%	8.33%	10.97%	28.42%
200	600	6	2	90	24	16	26.67%	27.09%	65.10%	3.33%	0.36%	20.03%
200	600	8	2	90	24	16	5.83%	8.79%	45.03%	0.00%	0.00%	9.50%
200	600	10	2	90	24	16	0.00%	2.11%	22.06%	0.00%	0.00%	2.77%
200	500	4	2	90	22	16	27.50%	42.62%	59.99%	5.00%	6.05%	36.56%
200	500	6	2	90	22	16	12.50%	14.72%	49.43%	3.33%	0.16%	25.54%
200	500	8	2	90	22	16	5.00%	3.57%	27.37%	0.00%	0.00%	11.20%
200	500	10	2	90	22	16	0.00%	0.53%	10.07%	0.00%	0.00%	3.01%

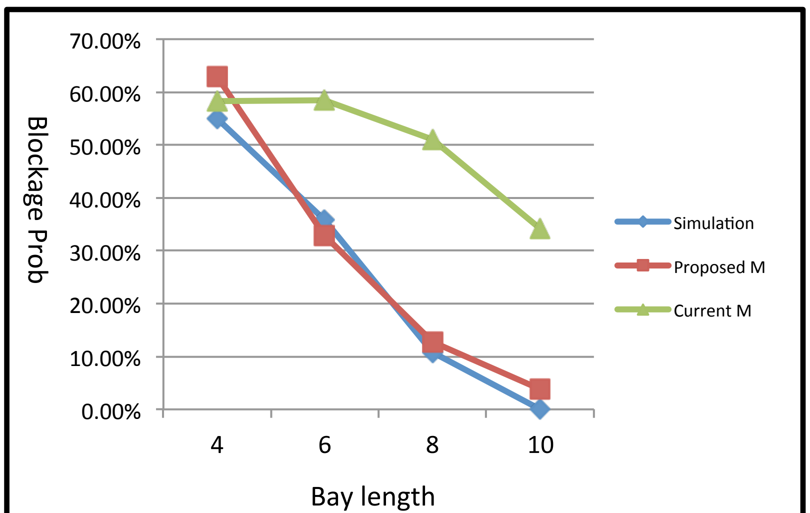
Results:

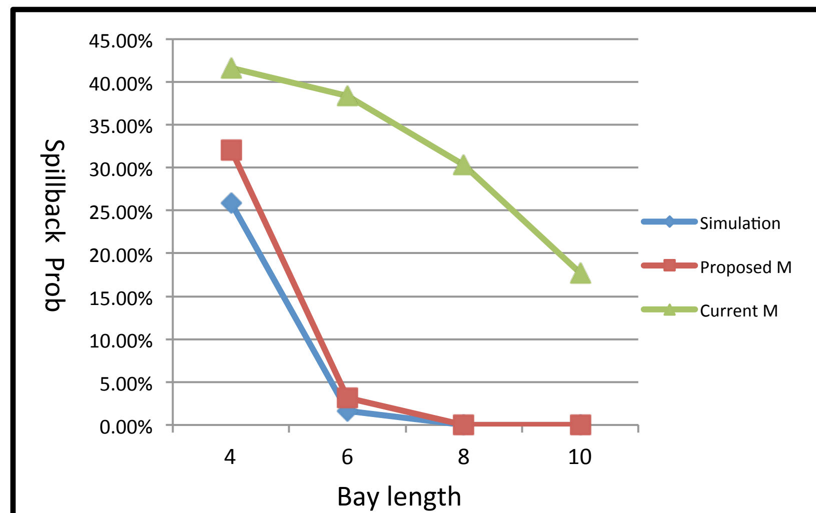
Case 1:





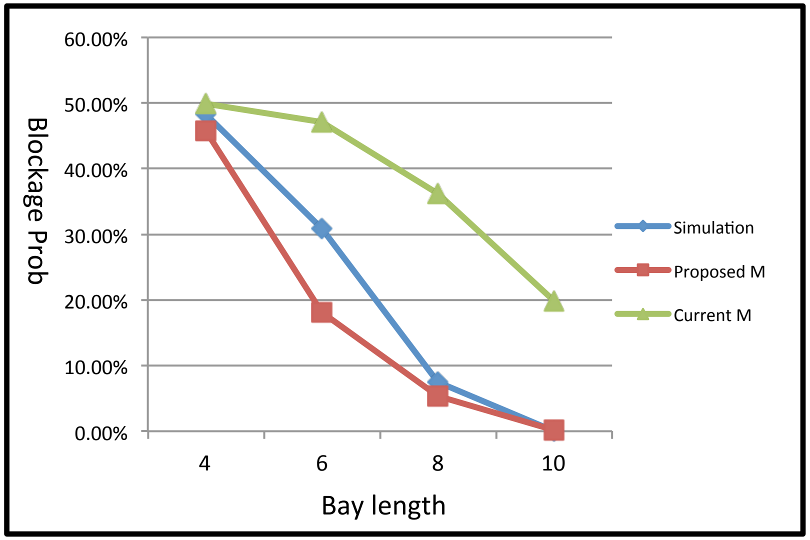
Case 2:

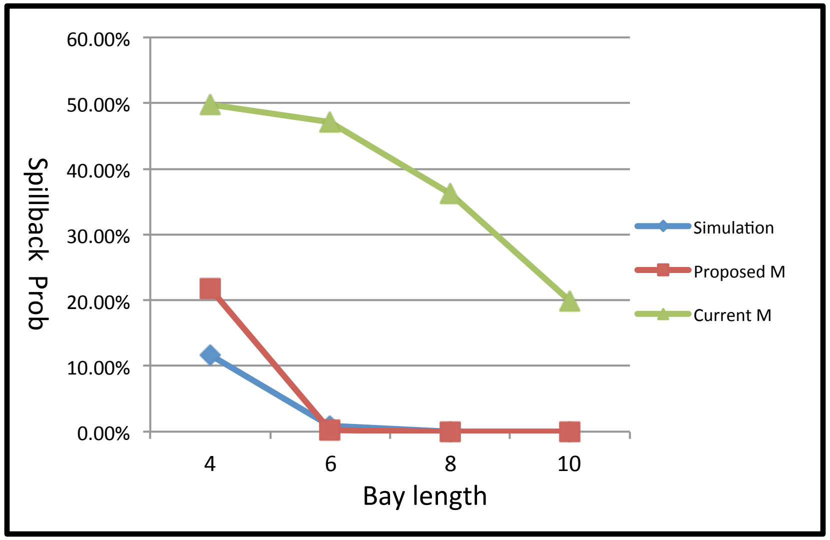




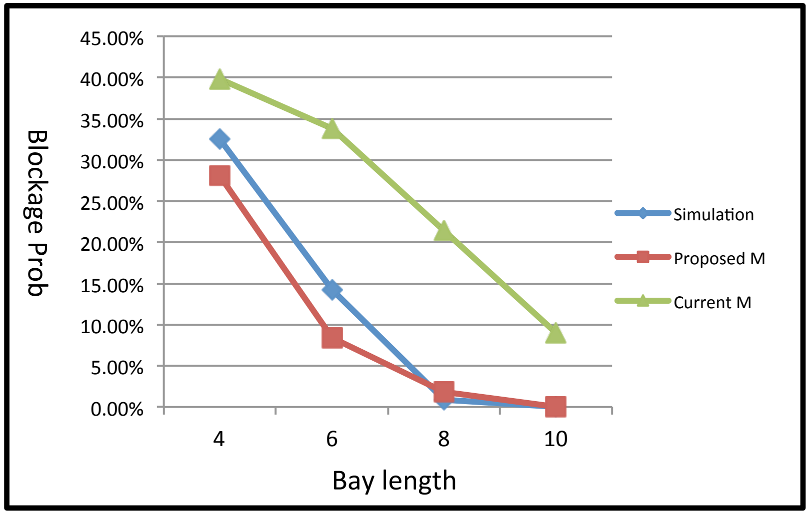
Results:

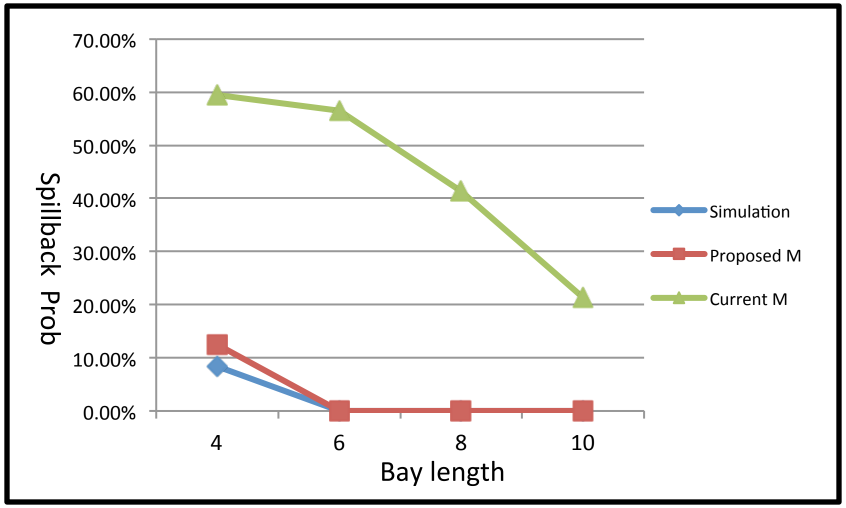
Case 3:





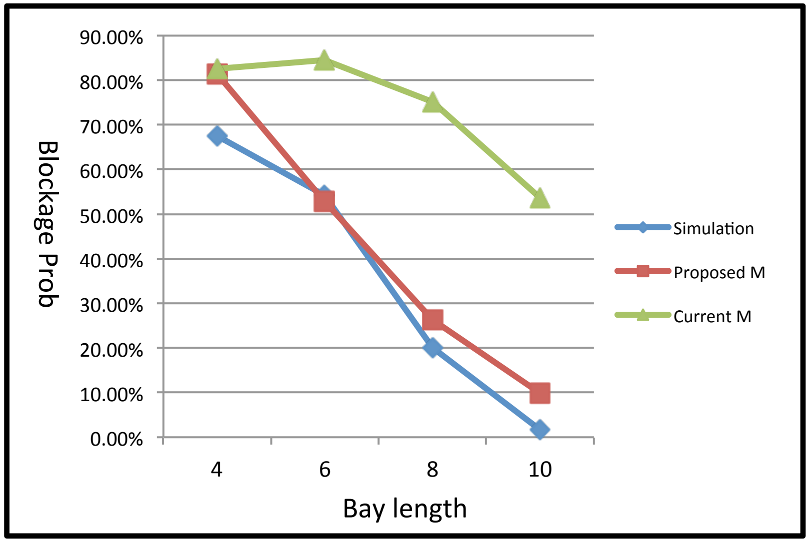
Case 4:

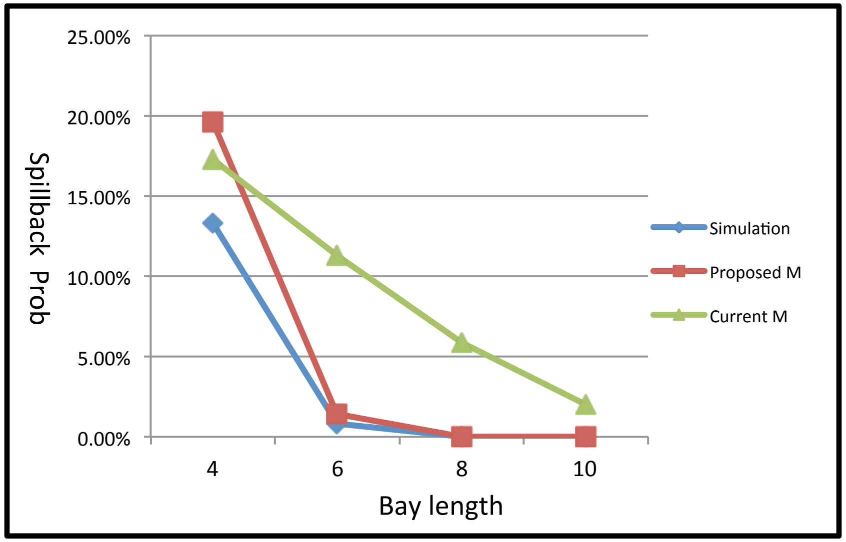




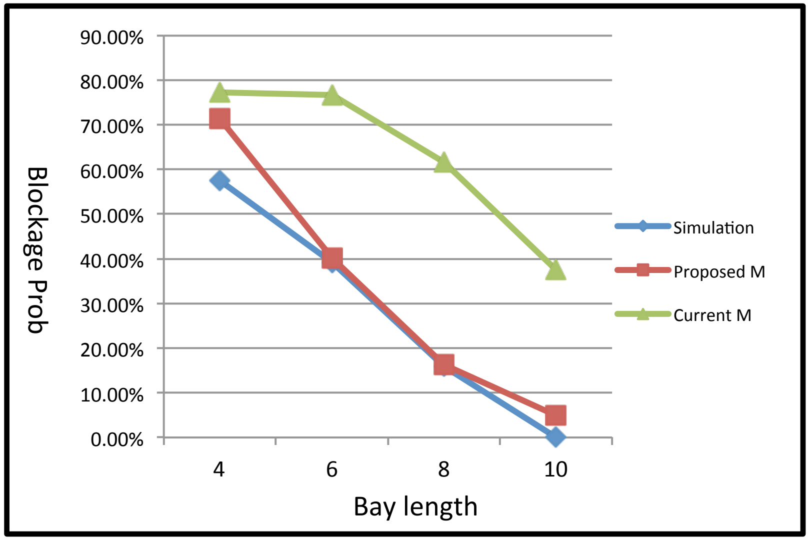
Results:

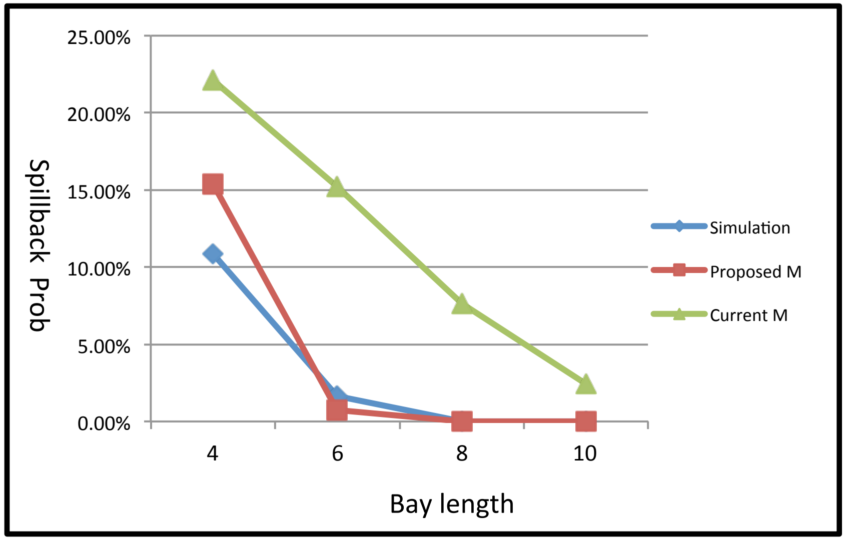
Case 5:





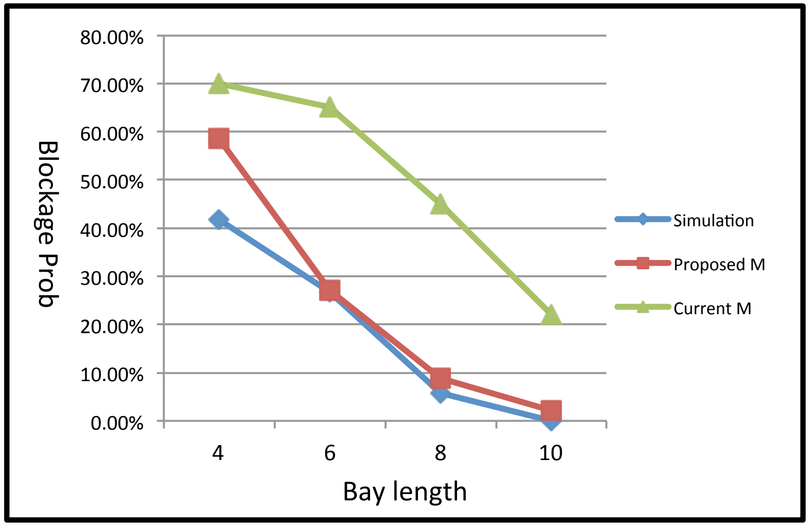
Case 6:

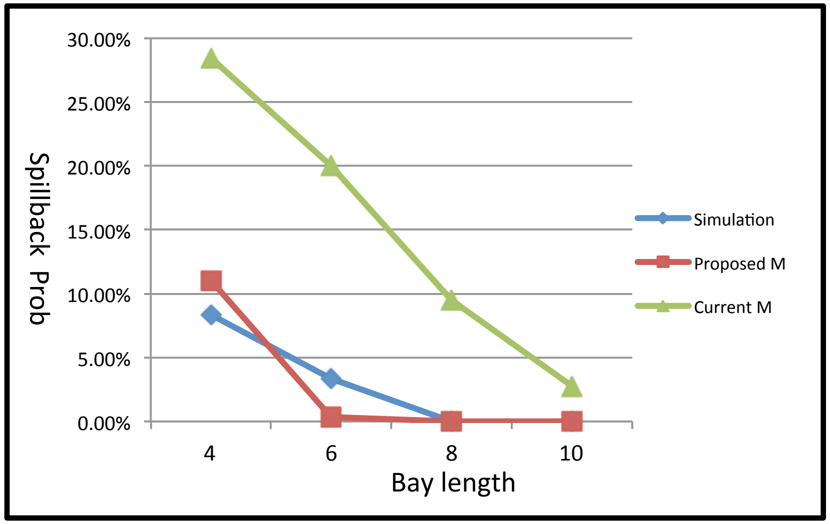




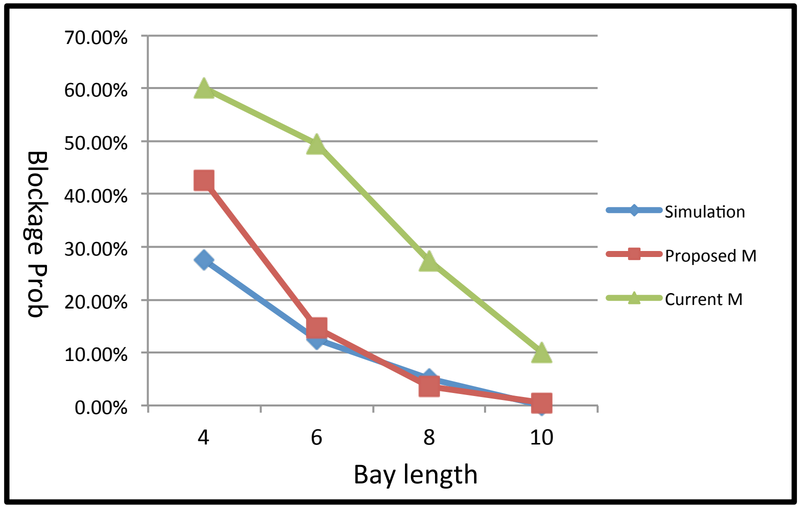
Results:

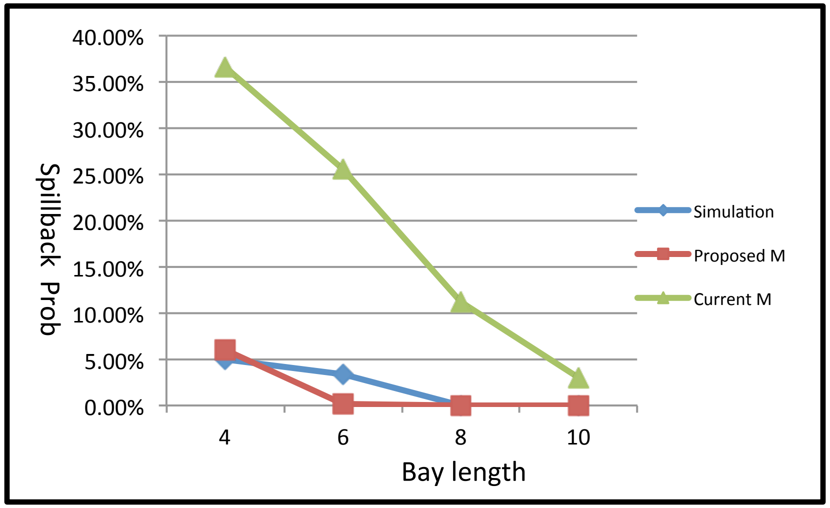
Case 7:





Case 8:





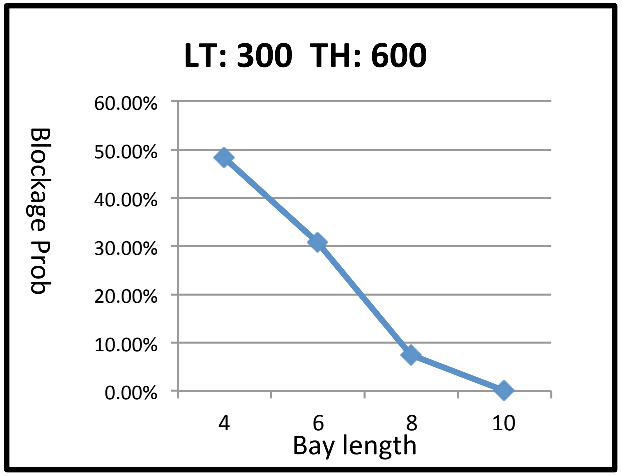
Results

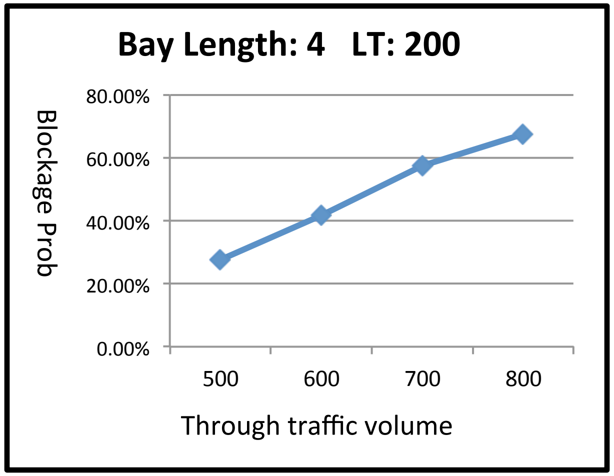
LT vph	TH vph	Bay length	# of TH lanes	CYCLE	TH GREEN	LT GREEN	Blocakge Prob	**LT Capacity**	Original LT Capacity	Spillback Prob	**TH Capacity**	Original TH Capacity
300	800	4	2	90	28	21	71.20%	329	467	42.70%	979	1244
300	800	6	2	90	28	21	42.40%	380	467	5.97%	1207	1244
300	800	8	2	90	28	21	19.10%	428	467	0.00%	1244	1244
300	800	10	2	90	28	21	6.53%	454	467	0.00%	1244	1244
300	700	4	2	90	24	21	62.85%	341	467	32.01%	896	1067
300	700	6	2	90	24	21	32.83%	399	467	3.20%	1050	1067
300	700	8	2	90	24	21	12.69%	440	467	0.02%	1067	1067
300	700	10	2	90	24	21	3.78%	458	467	0.00%	1067	1067
300	600	4	2	90	24	22	45.80%	384	489	21.74%	951	1067
300	600	6	2	90	24	22	18.06%	446	489	0.19%	1066	1067
300	600	8	2	90	24	22	5.36%	476	489	0.00%	1067	1067
300	600	10	2	90	24	22	0.12%	486	489	0.00%	1067	1067
300	500	4	2	90	21	22	28.12%	421	489	12.50%	875	933
300	500	6	2	90	21	22	8.42%	469	489	0.07%	933	933
300	500	8	2	90	21	22	1.80%	484	489	0.00%	933	933
300	500	10	2	90	21	22	0.00%	489	489	0.00%	933	933
200	800	4	2	90	27	16	81.31%	219	356	19.58%	1083	1200
200	800	6	2	90	27	16	52.90%	261	356	1.41%	1192	1200
200	800	8	2	90	27	16	26.38%	308	356	0.00%	1200	1200
200	800	10	2	90	27	16	9.81%	337	356	0.00%	1200	1200
200	700	4	2	90	26	16	71.39%	229	356	15.37%	1067	1156
200	700	6	2	90	26	16	40.17%	283	356	0.72%	1151	1156
200	700	8	2	90	26	16	16.29%	326	356	0.00%	1156	1156
200	700	10	2	90	26	16	4.90%	346	356	0.00%	1156	1156
200	600	4	2	90	24	16	58.63%	250	356	10.97%	1008	1067
200	600	6	2	90	24	16	27.09%	305	356	0.36%	1065	1067
200	600	8	2	90	24	16	8.79%	339	356	0.00%	1067	1067
200	600	10	2	90	24	16	2.11%	351	356	0.00%	1067	1067
200	500	4	2	90	22	16	42.62%	276	356	6.05%	948	978
200	500	6	2	90	22	16	14.72%	328	356	0.16%	977	978
200	500	8	2	90	22	16	3.57%	348	356	0.00%	978	978
200	500	10	2	90	22	16	0.53%	354	356	0.00%	978	978

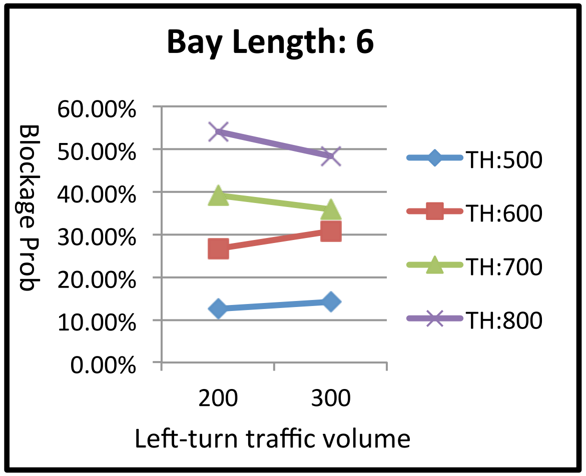
Findings and conclusions

Findings:

- For blockage situation:
  - a) the length of left-turn bay ⇧, the probability ⇩;
  - b) the through traffic volume ⇧, the probability ⇧;
  - c) the left-turn traffic volume ⇧, the probability ➡ .



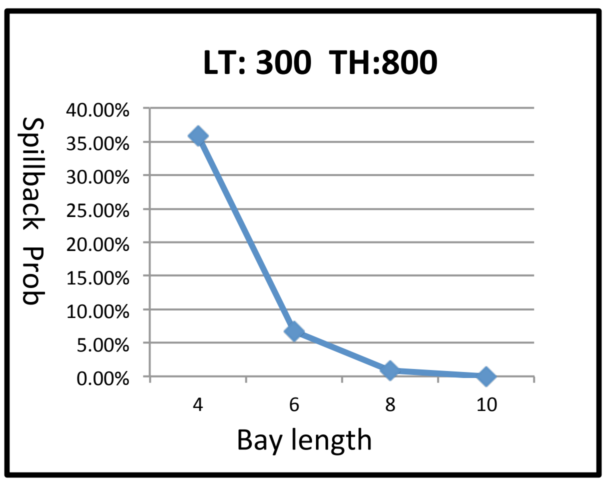


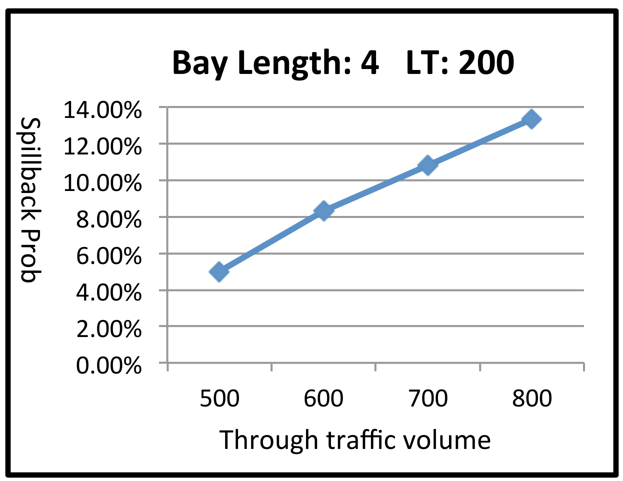


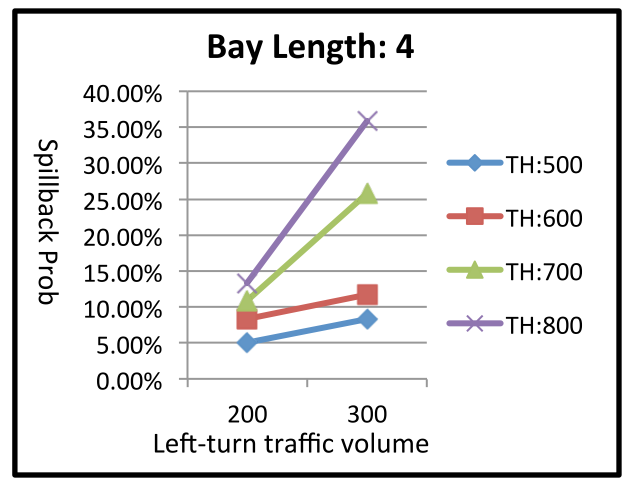
Findings and conclusions

Findings:

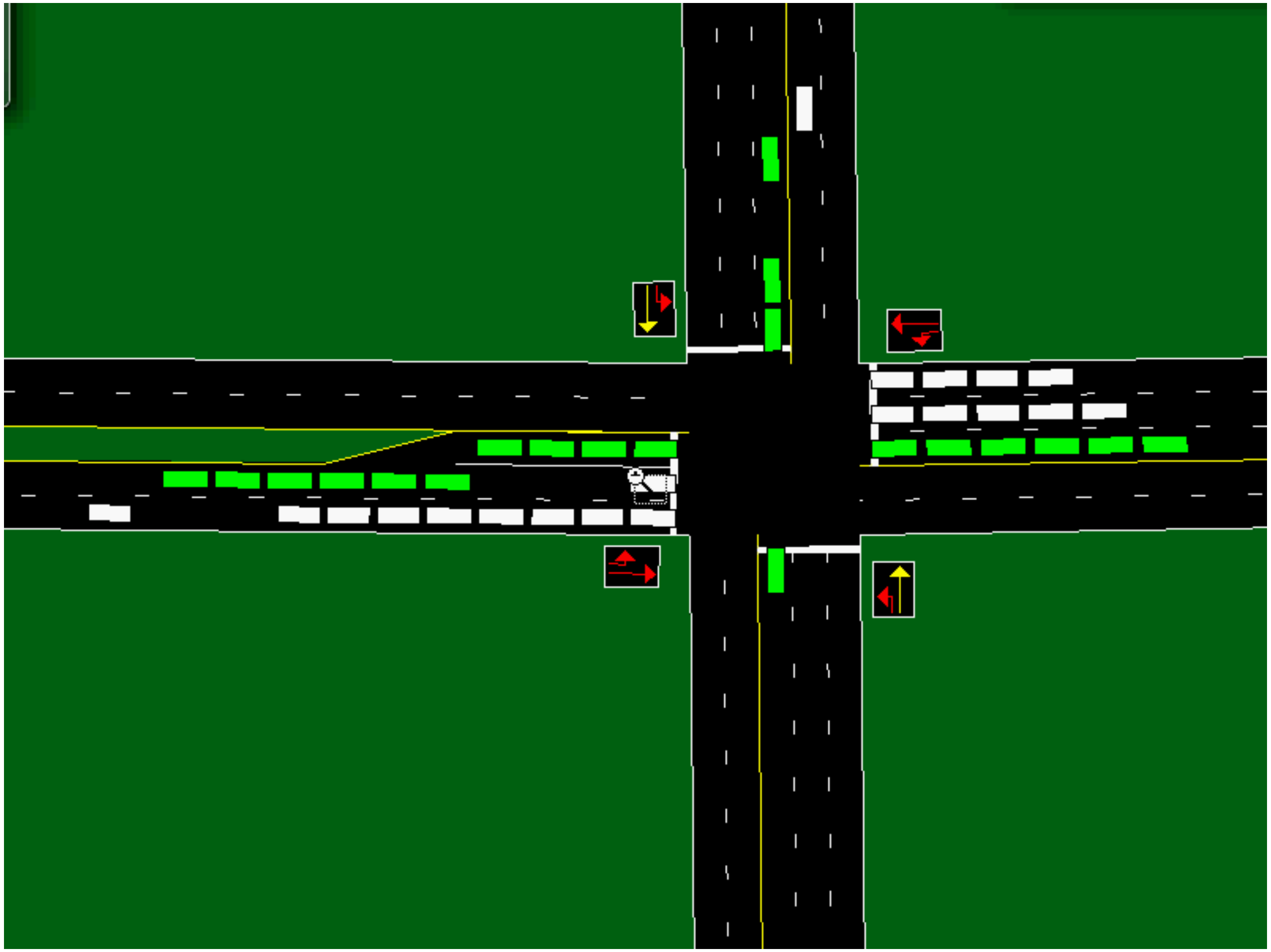
- For spillback situation:
  - a) the length of left-turn bay , the probability ;
  - b) the left-turn traffic volume , the probability ;
  - c) the though traffic volume , the probability .







Findings and conclusions



Findings and conclusions

Conclusions

1. The proposed model considers factors and natures that have not been included into the current models;

2. The proposed model shows better results compared with current models;

3. The proposed model needs more detailed input and assumptions.

Limitations and future work

- Limitations

1. No field data for the validation;
2. No data for the capacity validation;
3. Arrival patterns are assumed to be Poisson distribution, however in reality, the coming vehicles may not follow this assumption;
4. The proposed method is not easy to apply, because it needs some iterations to get the stable condition;
5. The proposed method doesn't consider the heavy traffic condition, which may cause the residual queue for through traffic after the green time;
6. The estimation of arrival rate for through traffic in adjacent through lane may need to consider more factors.

Limitations and future work

- Future work

1. Try to collect some field data and try to find ways to obtain the probabilities of blockage and spillback;

2. Try to figure out how to validate the capacity results from the model.

3. Try to enhance the estimation model about the arrival rate for through traffic in adjacent through lane;

4. Try to consider the heavy traffic condition into the model;

5. Try to consider the mixed vehicles(buses, trucks) into the model.

- Thank you!