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Surrogate safety assessment for a tight urban diamond interchange using micro-simulation

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Abstract: This paper presents development of a surrogate safety assessment method and its application to a real-life traffic engineering project. The Tight Urban Diamond Interchange (TUDI) is one of the most commonly used interchange types in the United States. Because of the complex traffic flow patterns, large turning movements and limited spacing between the traffic signals, TUDI is often a source of traffic accidents and bottlenecks. Although U-turns have proven to be beneficial to increase capacity, they also tend to substantially increase traffic conflicts and accidents around the interchange area. Installation of metering-type signals at the U-turn approaches of TUDI has recently been proposed by traffic engineers as a countermeasure to reduce traffic conflicts. In this study, the time-to-collision (TTC) and the post-encroachment-time (PET) are used as the surrogate safety indicators to evaluate the safety level of a TUDI. Several simulation plug-in modules are developed to extract the surrogate safety indicators for safety assessment of installing metering type signals. The results show that although applying a metering signal in U-turn areas will decrease the capacity, it has a positive effect on the intersection safety.

Keywords: surrogate safety measurement, traffic simulation, diamond interchange
1. Introduction

The Tight Urban Diamond Interchange (TUDI) is one of the most commonly used transportation facilities serving as the interconnections between the freeway systems and the surface street arterials. Normally, a TUDI has two closely spaced intersections where the ramps terminate at the cross street. Comparing to other transportation facilities, TUDI is often the source of traffic accidents and bottlenecks due to its complex traffic flow patterns, high turning movements and limited spacing between the traffic signals.

Traditional methods for safety assessments at signalized intersections and interchanges are usually based on statistical analysis, which relies largely on historical traffic collision data. For example, many researchers use multiple regression models to predict accident frequencies for the entire interchange areas (Morgenstein and Edmonds, 1978; Hauer et al. 1988; Bauer and Harwod 1998; and Wang et al. 2003). In their research, traffic volumes were found to be a key variable in predicting interchange accident experience. Bared et al. (2005) compared accident frequencies of single point diamond interchanges (SPI) with tight diamond interchanges (TDI). They used negative binomial statistical model to estimate safety level of TDI.

Statistical models are advantageous in many aspects in safety studies, however, they are not suitable for the short-term “before and after” analyses which are often required by traffic engineers when seeking for the best solution from multiple alternatives. Surrogate safety assessment is then considered as an alternative which can provide a quantitative and qualitative indication of the prevailing traffic safety level in road sections. Traffic conflicts technique (TCT) is the most prevalent approach, widely used for surrogate safety measures. A Conflict is defined by Cooper and Ferguson (1976) as “An observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged.” Migletz et al. (1985), Chin and Quek (1997), and Risser (1985) conducted their research by examining the relationship between conflicts and traffic accidents. The general consensus that has been reached in their findings was that higher rates of traffic conflicts could indicate lower levels of safety of the road facility.
Time-to-Collision (TTC) is the primary surrogate safety indicator which was originally suggested by Hayward (1972). TTC based on the leading-following vehicle pairs is defined as the time left to a collision between two vehicles if they maintain the same speed on the same road. Archer (2005) pointed out that the actual TTC-value used represents the minimum time to collision during the entire conflict event rather than the value which is recorded at the time when evasive action is taken.

Post-Encroachment Time (PET) is the further variation of TTC. It measures the temporal difference between two vehicles as they pass over a common spatial point or area. The main difference between PET and TTC is the absence of the collision course criterion in PET. Archer (2005) indicated that since there is no requirement for the existence of collision course, PET is more useful in measuring transversal conflicts. In addition, those events with similar trajectories will always be involved in the collision course if the follower’s speed is faster than the leader’s speed. Gettman and Head (2002) described a different definition of PET by involving the evasive action. Their concept is not subject to the limitation of transversal crossing maneuvers and preserves the intuitive simplicity of the fundamental PET concept.

Minderhood and Bovy (2001) have proposed two alternative proximal safety indicators based on the concept of TTC: Time Exposed (TET) and Time Integrated TTC (TIT). These indicators represent the duration of time under a designated TTC-threshold. Other surrogate safety indicators such as gap time (GT) and deceleration rate (DR) were also used to indicate relative safety level.

With advances in computing technology and the ever-increasing power of personal computers, many sophisticated simulation models have been developed in the area of transportation engineering. However, few studies reported in the current literature have information about successful stories of application of surrogate safety indicators to real-life projects. One of the efforts recently undertaken was by Gettman and Head (2002), who developed a Surrogate Safety Assessment Module (SSAM) to compute safety indicator measures and extract and analyze simulation output data. Kosonen (1999) utilized an adapted HUTSIM micro-simulation to identify and record traffic conflicts. Archer (2005) also developed the module based on the VISSIM model to estimate level of safety at a suburban T-junction.
The purpose of this paper is to share our experience with the surrogate assessment method from a real-life application. It includes identifying and extracting surrogate safety indicators from microscopic simulation, analyzing the proposed engineering approach by the indicators, lessons learned, and suggestions for implementation. The simulation software used in this study is PARAMICS developed by Quadstone Inc. The model network for this research is a tight diamond interchange at the Slide Road and the South Loop 289 located in the city of Lubbock, Texas. It is one of the intersections with high accident rates which the city traffic engineers have been struggling with. The collision rate at this location far exceeds the number predicted by statistical safety models. The geometry of the intersection was redesigned along with various new traffic signal timing plans for the past few years; however, no apparent safety improvement was achieved.

With the latest traffic and safety data, recent focus has been placed on investigating the design and operational issues of the U-turn areas as well as the impact of the U-turn movements to the entire interchange area. The research has found that although provision of U-turn is beneficial to capacity, it also tends to create extra conflict events around the interchange area and increases the risk of collisions substantially. Installation of metering type signals at the U-turn areas was proposed by local traffic engineers to regulate traffic flow and reduce conflicting events. The surrogate method proposed in this paper was applied to investigate this typical “what if” problem. The safety and capacity performance of the interchange before and after the introduction of the metering type signals are evaluated through the development of plug-in modules in PARAMICS. The surrogate safety indicators including TTC and PET were extracted from simulation outputs, based on which the safety analysis and statistical evaluation were conducted. The findings of this research conclude that adding metering type signals to the U-turn areas is positive in terms of reducing crossing type conflicts but less effective for the rear-end and lane-changing conflicts.

2. Developing surrogate safety indicators through application programming interface
Microscopic simulation has been widely used in transportation studies. It mimics movements of individual vehicles and is advantageous in assessing operational strategies without the risk of disrupting actual traffic flows. Microscopic simulation also proves to be cost-effective in collecting safety surrogates. The simulator used in this study is PARAMICS (PARAllel MIcroscoPic Simulation), a mainstream simulation model developed by Quadstone Inc. PARAMICS is a suite of microscopic simulation tool used for modeling the movement and behavior of individual vehicles on urban and highway road networks. It offers detailed modeling for many components of the traffic system. Not only the characteristics of drivers, vehicles and the interactions between vehicles but also the network geometry can influence simulation results. In order to introduce the metering type signal to the simulation and obtain surrogate safety indicators, several models were developed and interfaced with PARAMICS’s built-in modules through the Application Programming Interface (API) programming. API programming is a practical way for users to enhance the capabilities of a micro-simulator. PARAMICS provides users with an API library that include a set of interface functions, which can be used to access its core models.

2.1 Simulation of the diamond interchange

Introducing a metering signal control to the U-turn lanes is one of the alternative solutions that could overcome the previously described safety problems during peak periods. However, the algorithm of metering signal control, its operation details and its impact on all road users need to be carefully considered before implementation.

At a diamond interchange, the two traffic signals are typically controlled by a single signal controller. Figure 1(a) shows the standard signal phase design, which includes the standard eight phases (except for Φ3 and Φ7). Each signal phase controls a particular traffic movement. The two internal through movements are controlled using overlap phases, A and B.

The traffic signal controller at the subject diamond interchange runs the phasing scheme (TTI 4-phase) shown in Figure 1(b). TTI 4-phase uses a lead-lead phasing sequence, i.e., the left-turn movements lead the through movements on both sides of the interchange, and it is aimed at minimizing
internal queues. This phasing scheme is used at most closely-spaced diamond interchanges to eliminate vehicle stopping within the interchange.

As aforementioned, the objective of applying the metering type signal control at U-turn lanes is to regulate traffic flow released into the frontage roads from the interchange and reduce the conflicting events created by the U-turn movements. The tested metering control algorithm was integrated with the TTI-4 phase control plan based on the characteristics of the U-turn movements. The layout of the metering type signal with the detectors is given in Figure 2.

The U-turn metering signals are implemented on a time-of-day basis since they are required only during peak traffic periods. They operate in two states according to the existence of the movements that are conflicting with the U-turn movements (e.g., the through movement from the frontage road).

Because the interchange is controlled by the TTI-4 phase plan, the metering signal must be designed to align with it. The first step of the metering control is to check the state of the signal for determining whether there are conflicting streams. In Figure 1(a), U1 and U2 represent the two U-turn movements. The conflicting streams for U-turn movement U1 are the frontage movement Φ8 and the internal left turn movement Φ5; the conflict streams for the U-turn movement U2 are the frontage movement Φ4 and the internal left turn movement Φ1. There is no reason to stop the U-turn movement when there is no conflicting traffic movement on the frontage road or internal left turn movement. Thus the metering signal will show green when U-turn movement does not conflict with other traffic movements. During the time when one or more major conflicting movements exist, the metering signal will release vehicles at a fixed metering rate. Two signal indications, green and red, will be provided by the metering signal. The cycle length is pre-defined as a required data input. In this study, the cycle length is 10 seconds. One-car-per-green is applied. The assumption is that the green time for one vehicle to pass the metering signal is 2 seconds. Therefore, the red time is 8 seconds. The detector for sensing the presence of a vehicle allows the signal to rest on red. The metering signal control algorithm is shown in Figure 3.
2.2 Surrogate safety indicators in simulation

Most microscopic simulation models are developed for the purpose of analyzing the capacity performance of transportation facilities. They normally include built-in features such as car-following, lane-changing, and gap-acceptance models. A surrogate safety assessment method first requires extracting the selected surrogate safety measures from simulation for the assessment of safety levels. The Time-to-Collision (TTC) and Post-Encroachment Time (PET) are found to be effective for this purpose.

**Time-to-Collision (TTC)**

A prerequisite condition for calculating the TTC value is to track the entire course of the identified conflict events. In this study, the conflict events are assumed to occur between two road-users engaged in a collision course unless at least one of them performs evasive action. Therefore, the conflict events counted in the simulation do not include those that involve more than two vehicles and the single vehicle crashes.

The collision course indicates a common temporal and spatial conflict point if the courses of the two-vehicle pair remain unchanged. First, the existence of a collision course must be verified. There are several different evasive actions a driver could use, such as deceleration, lane change, and acceleration. Without loss of generality, only deceleration is considered. The conflict events are classified into three types: rear-end, crossing, and lane-changing.

**Rear-End-TTC Conflict Event** The leading and following vehicles are in the same lane. The leading vehicle causes the following vehicle to decelerate to avoid collision. This type of conflict event is a potential cause for the rear-end collision.

Rear-end-TTC is calculated by equation (1). Where, TTC* is the threshold value of the rear-end-TTC, which separates critical safety situations from those in which the driver remains in control. If the calculated Rear-end-TTC of one conflict event is smaller than the threshold value TTC*, then the
rear-end-TTC value will be stored. It is flexible for the researchers to choose a realistic value, or several values for testing. In this study, the threshold is 2 seconds.

\[
TTC_i = \frac{Xl_i(t) - Xf_i(t) - \frac{1}{2}(Ll_i + Lf_i)}{\dot{X}l_i(t) - \dot{X}f_i(t)} \quad \forall \ \dot{X}i(t) > \dot{X}l_i(t) \text{ and } TTC_i < TTC^* \\
Xf_i(t): \text{the position of the following vehicle at time } t \text{ in event } i \\
Xl_i(t): \text{the position of the leading vehicle at time } t \text{ in event } i \\
\dot{X}f_i(t): \text{the speed of the following vehicle at time } t \text{ in event } i \\
\dot{X}l_i(t): \text{the speed of the following vehicle at time } t \text{ in event } i \\
Ll_i: \text{the length of the leading vehicle} \\
Lf_i: \text{the length of the following vehicle} \\
TTC^*: \text{the threshold value of TTC (2.0s)}
\]

A PARAMICS rear-end-TTC plug-in module was developed. At each simulation step, the plug-in module checks each leading-following vehicle pair in the network. In a rear-end conflict event, if the speed of the following vehicle is greater than that of the leading vehicle, there will be a collision course. Under such conditions, if the following vehicle is braking, one rear-end conflict event will be created and the related information of the involved vehicles ID, speed, position, acceleration, and current simulation time will be recorded.

In the next simulation step, the information of the traced vehicle pair for each conflict event continues to be updated. If a collision course does not continue (the follower’s speed is less than or equal to the leader’s speed), the conflict event is over. The PARAMICS rear-end-TTC plug-in module stores the involved vehicle’s ID, the smallest rear-end-TTC value, conflict location, conflict time and the maximum deceleration rate of the following vehicle for each conflict event.

**Crossing-TTC Conflict Event** Crossing vehicle is in conflict with the through vehicle. This type of conflict events usually causes potential angle collisions.

In a TUDI area, most of the crossing conflict events are concentrated in the U-turn area. The crossing conflict zone in the PARAMICS crossing-TTC plug-in module is defined as shown in Figure 4.
Once a U-turn vehicle enters this zone, the crossing-TTC module will be called and the existence of a collision course between the U-turn vehicle and through vehicle will be checked. If a collision course exists and the through vehicle decelerates to avoid a collision, a conflict event is recorded and the crossing-TTC is calculated based on the projected trajectories of the two involved vehicles.

**Lane-Changing-TTC Conflict Event** The lead vehicle changes lanes, conflicting with the following vehicle in the target lane due to an insufficient gap. This type of conflict causes the potential for rear-end collision or angle collision.

The PARAMICS lane-changing-TTC plug-in module is called when a vehicle initiates a lane-changing behavior. The module will check the existence of a collision course between the lane-changing vehicle and the following vehicle in the target lane. Conflict events will be recorded until the leading vehicle completes its lane-changing action. Calculation of the lane-changing-TTC value is similar to that of the rear-end-TTC module.

*Post-Encroachment Time (PET)*

The Post-Encroachment Time (PET) is a further variation of the TTC. Due to the absence of the collision course criterion, PET is easier to extract in simulation models than TTC. PET-measurement only needs a fixed conflict point rather than one that changes dynamically. PET is better suited to measure the relative safety level for crossing conflict than rear-end or lane-changing conflict events. Therefore, the PARAMICS crossing-PET plug-in module is developed for U-turn conflicting areas.

As shown in Figure 5, a detector is placed in the conflicting point between the U-turn movement and the through movement. The temporal difference between the two movement road-users over the detector needs to be recorded and related information stored in the database.

3. **Data collection and model calibration and implementation**
3.1 Data collection

Videotaped traffic counts at the subject TUDI were collected during the p.m. peak hour (4:30~5:30) in June and October, 2005. The aerial photographs and as-built construction CAD drawings were provided by the City of Lubbock, which was used to establish the network geometry. The fixed-time TTI-4 diamond phasing plan was coded in simulation along with the intersection geometry. Detailed description of the data collection process is beyond the scope of the paper and thus eliminated.

3.2 Model implementation

Road Network

The geometry of the interchange was coded based on the bitmap image of the aerial photograph of the area. Detailed information of each intersection node was then coded based on CAD drawings and field measurements. The resulted PARAMICS simulation network is shown in Figure 6.

Traffic Demand Matrix

Traffic demand is defined by the origin-destination (O-D) matrix in PARAMICS. The network considered for this study was modeled with eight zones as shown in Figure 6. Table 1 shows the O-D movement data derived from the turning movement counts at the study site.

Model Calibration

Both the TTC and the PET are quite sensitive to driver behavior. Realizing that unrealistic lane changing behavior will dramatically increase the conflicting events, the model calibration is focused on adjusting the simulation model based on the observed traffic conditions from the video tapes.

PARAMICS controls driver behavior mainly through two parameters: aggression and awareness. The simulator randomly assigns values of aggression and awareness to the driver of each vehicle on a scale of 1-8. These parameters have an effect on such quantities as target headway, top speed, propensity to change lane and gap acceptance of the individuals. One can alter the type of statistical distribution (i.e.,
Normal, Poisson) of the aggression and awareness parameters to reflect regional variations in driver behavior. With the assigned aggression and awareness parameters, three interacting models then control the movement of each vehicle: a vehicle following model, a gap acceptance model, and a lane changing model.

In addition to the two main parameters, the following parameters and methods can also be used to adjust driver behavior in PARAMICS.

**Signpost**: the term signpost is used to include hazards as part of the driver behavior representation of PARAMICS. A hazard defined as a network characteristic or feature that may cause a vehicle to change lane, for example a road narrowing (lane drop) or a signalized junction/intersection.

**Next lane**: define the lane mapping for vehicles transferring between links.

**Familiarity and Patience**: familiarity and patience primarily affect route choice but they also have effects on driver behavior in reactions to signposts, look-a-head reaction times for car following etc.

**Accurate coding of network feature**: The PARAMICS driver behavior model interacts with the network geometry, causing changes in vehicle speed and position.

All above parameters/methods were carefully adjusted/applied to accurately reflect the actual road and observed vehicle movements.

Since PARAMICS is a stochastic simulation model which randomly releases vehicles, assigns vehicle type, selects a vehicles’ destination route, as well as determines the driver behaviors, the surrogate safety indicators must be collected during multiple simulation runs in order to make reliable simulation results. The number of simulation runs is estimated by the following equation:

\[ N \geq \frac{s^2 t_{\alpha/2}^2}{\varepsilon^2} \]

- \( N \): number of simulation runs
- \( s^2 \): variance
- \( t_{\alpha/2} \): critical value for t distribution at 100(1 - \( \alpha \)) confidence level
- \( \varepsilon \): maximum error

\[ (2) \]
Based on 20 trial runs, at 95% confident level, 12 simulation runs are required for this study with 2 conflict event errors.

4. Evaluation

4.1 Safety evaluation

Two control scenarios were simulated based on the combination of the diamond interchange control and U-turn metering signal control: (1) without metering signal control in the U-turn areas; (2) with metering signal control in the U-turn areas.

The safety measure from simulation is focused on two surrogate safety indicators, TTC and PET, as described in Table 2. Two-sample t-test is performed to check the effect of employing the metering signal. The simulation result shows that there is no statistical difference in the total number of the rear-end-TTC and the lane-changing-TTC events. However, the crossing-TTC events are reduced from 44.1 to 33.3 and the crossing-PET events are also reduced from 76.9 to 59.9, a 22.6% reduction. The average crossing-TTC value is increased from 1.49 seconds to 1.53 seconds; the crossing-PET value is increased from 1.66 seconds to 1.72 seconds. Based on the results shown in Table 2, implementing the metering signals in the U-turn areas has demonstrated significant impact to safety performance, especially in terms of reducing the crossing conflicts.

It is also noted that the rear-end-TTC conflict is the major type of conflict in both scenarios. However, the rear-end-TTC type of conflict event in the surrogate method has higher percentage than that observed in the field. The reason for this phenomenon is partly due to the constraints of the simulation model in that the rear-end conflict is relatively easier to capture than other types in simulation and some lane-changing conflict events may be misrecognized as rear-end conflicts. Another reason is the determination of the conflict area. The rear-end conflicts are tracked from the whole diamond interchange area. However, the crossing conflicts are only focused on the conflict zone as defined in Figure 5 due to the inherent characteristics of the traffic streams and the type of signal control at diamond interchange.
As shown in Figure 7 (a), 10 locations are classified to show the distribution of the rear-end-TTC conflict events in the study area. Figure 7 (b) shows that location 5 (East Frontage) and 6 (West Frontage) are the most dangerous rear-end conflict areas. There is no strong evidence to support that installation of metering signal has significant effect on the distribution of the rear-end-TTC conflict events under current traffic flow conditions.

4.2 Performance evaluation

On the capacity part, Table 3 shows that the difference in the average delay at the primary approaches is not significant with and without the metering signal. However, the average travel time is increased from 93.6 seconds to 105.4 seconds for the west U-turn movement (zone 3—>zone 5); the average travel time is increased from 66.7 seconds to 78.4 seconds for the east U-turn movement (zone 6—> zone 8). The installation of the metering signals causes higher travel delays to the U-turn movement, which indicates that the capacity of TUDI will be decreased with the metering signal.

5. Concluding remarks

A surrogate safety method using microscopic simulation is presented in this paper for evaluation of the effectiveness of installing metering type signals in the U-turn areas of a TUDI. Simulation Plug-in modules were developed to model the metering type signals and to extract surrogate safety indicators (TTC and PET). The safety and capacity performance of the interchange before and after the introduction of the metering type signals were evaluated. It was concluded that adding metering type signals to the U-turn areas had positive effect in reducing crossing type conflicts, and was less effective in reducing rear-end and lane-changing conflicts. It is no surprise that a metering signal would significantly increase the average travel time of a U-turn movement. The trade-off between the intersection capacity and the level of safety should be considered before such an installation.

The purpose of this study is not only to demonstrate the evaluation process of a specific engineering countermeasure, but also shed light on how the surrogate safety assessment method can be
designed and applied to real-life traffic engineering projects. Further study is currently underway to
develop more accurate models to track the conflict events and to test performance of the metering signal
control algorithm on broader traffic flow and geometric conditions.
References


Hayward, J. (1972). Near miss determination through use of a scale of danger. Publication. TTSC-7715, Pennsylvania State University, Penn., USA.


Fig. 1. (a) Diamond interchange standard phase design
(b) TTI-4 phase and traffic progression diagram

Fig. 2. U-turn metering signal layout
Fig. 3. U-turn metering signal control algorithm

Fig. 4. Crossing conflict zone in U-turn area
Fig. 5. Post-Encroachment (PET) measurement detector in U-turn area

Fig. 6. The coded simulation network
Fig. 7. (a) Events location for rear-end conflicts
(b) Distribution of rear-end conflict events
Table 1. OD demand of the TUDI (in veh/h)

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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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Table 2. Two-sample number of conflict events t-test results

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<tr>
<th>Conflict Type</th>
<th>Average TTC and PET (s)</th>
<th>Number of Conflict Events</th>
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<td></td>
<td>With Metering Signal</td>
<td>Without Metering Signal</td>
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<tr>
<td>Rear End-TTC</td>
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<td>1.24</td>
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<tr>
<td></td>
<td>p-value</td>
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<td></td>
<td>p-value</td>
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<td>Lane-Changing-TTC</td>
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<td></td>
<td>p-value</td>
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<td></td>
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* Significant difference at 95% confident level
Table 3. Comparison of average travel time

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<th>O-D Movement</th>
<th>Average Travel Time (s)</th>
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<td>With Metering Signal</td>
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<tr>
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<td>Without Metering Signal</td>
<td></td>
<td>Without Metering Signal</td>
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<td>Mean p-value</td>
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<td>56.7</td>
<td>0.248</td>
</tr>
<tr>
<td>3-&gt;1</td>
<td>Mean p-value</td>
<td>126.7</td>
<td>0.585</td>
</tr>
</tbody>
</table>

* Significant difference at 95% confident level