Evaluation of Intersection Collision Warning System Using an Inter-vehicle Communication Simulator

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***Abstract*— An inter-vehicle communication (IVC) simulator has been developed to evaluate an intersection collision warning system. Various representative intersection collision scenarios are simulated. The physical and Media Access Control layer of the wireless communication network are modelled in the IVC simulator for transmission of collision warning messages. The results show that such a collision warning strategy is a viable way for reducing the collisions at the intersections.**

I. Introduction

Intersection collisions constitute approximately 26% of all crashes in the United States [6]. Moreover, about one fourth of fatal crashes occur at or near intersection [5]. Different from longitudinal and lateral collisions that occur in a single direction of traffic flow, most intersection collisions involve vehicles in different crossing path directions. To avoid intersection collisions, necessary information of the intersection vicinity needs to be provided to drivers beforehand. For example, a driver should be informed of imminent collisions when approaching or crossing intersections. Various services and technologies can be used to provide the driver with assistance in avoiding collisions at intersections due to inattention, faulty perception, obstructed views or intoxication [2]. The communication systems that are prevalent in intersection collision warning and avoidance systems are mostly based on Cooperative Infrastructure-Vehicle Communications technologies. These types of systems consist of vehicles continually relaying information to a beacon located in the approaching intersection. [1], [16] A more flexible method to exchange these information is through Inter-Vehicle Communication, because no infrastructure is needed in intersections. In this paper, we report on a IVC simulator for intersection collision warning systems. It is assumed that DGPS provides data to all the vehicles and all the 4-wheeled vehicles have the access to the navigation system. At a certain distance from the intersection, the vehicles begin to broadcast their locations, directions of travel and speeds. An ad-hoc network is established for the transmission of messages. To evaluate the effects of this systems, we developed the IVC simulator, which consists of a Vehicle Traffic Simulator (VTS) and a Wireless Simulator (WS), as shown in Figure 1.

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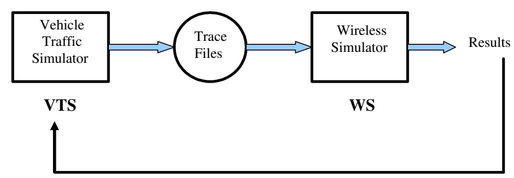


Fig. 1. IVC Simulator

The paper is organized as below: Section I gives an introduction. Section II describes the VTS. Shadowing effect is discussed in Section III. Section IV focused on the evaluation of protocol design and standards chosen. Simulation and the comparison of parameters change will be presented in Section V. Conclusions are drawn in Section VI. This paper discusses the traffic aspects of IVC, as compared to physical and MAC aspects, which can be found in a companion paper [10].

II. Vehicle Traffic Simulator

The Vehicle Simulator is implemented as a modular simulation system with an objected-oriented flavor using MATLAB. VTS is set up to simulate different intersection collisions scenarios. As shown in Figure 2, the VTS framework consists of three modules, which are Vehicle Characteristic Input, Intersection Collision Simulator, and Scenario Input, respectively.

A. Vehicle Characteristic Input

Vehicle characteristic input module includes the user-specified information. There are five kinds of vehicle characteristics defined in the simulator: 1) vehicle classification,

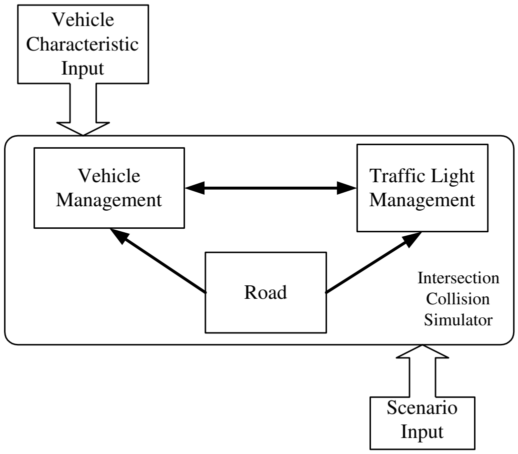


Fig. 2. Vehicle Traffic Simulator

2) vehicle size, 3) vehicle speed, 4) vehicle origin and destination, and 5) vehicle flow rate.

1) Vehicle Classification (Length, Width): Vehicle size is an important parameter that affects intersection collisions. For example, in left-turning scenario, an off-sight intersection collision is mainly due to an oversized vehicle which blocks the sight of other vehicles.

2) Vehicle Speed: Three kinds of personalities of drivers, conservative, normal and aggressive, are modelled. Each vehicle enters the system with a speed randomly assigned according to the following equation [9], [12].

$$V = \begin{cases} SpeedLimit - 5 & & \text{Conservative} \\ SpeedLimit & m/s & \text{Normal} \\ SpeedLimit + 5 & & \text{Aggressive} \end{cases} \quad (1)$$

The initial vehicle speeds are then normally distributed with the mean value equal to the speed limit and the standard deviation equal to 5 (both in m/s unit). Since a motorcycle rider is usually more aggressive, the motorcycle is always assigned a higher speed. (refer to Section III)

3) Vehicle Origin and Destination: Each vehicle is deterministic on its destination. When vehicle enters the system, the driver already decide whether to make right turn, left turn or go straight at the intersection. In practice, this can be implemented by using a GPS receiver and a Navigation system. Note, motorcycle has GPS receiver only.

4) Vehicle Flow Rate: Based on the car-following and platoon theory, the entering characteristics of the vehicles into the intersection area can be viewed as a Poisson process. The Poisson arrival rate, therefore determines the vehicle volume of the whole system.

B. Motorcycles

Compared with other vehicles, motorcycles are small-size, low- height, lightweight and performance oriented motorized vehicles. [7] Besides, motorcycles also possess additional distinct, which may cause deficiencies for intersection warning systems. Throughout the observations and exposure of the data, some deficiencies are summarized as follows [8]:

1) Because of its small size, a motorcycle can be easily hidden by objects, such as other vehicles, bushes, fences, bridges, etc.
2) The view of the motorcycle is limited by glare or obstructed by other vehicles.
3) Intersections are the most likely place for the motorcycle accident, with the other vehicle violating the motorcycle right-of-way, and often violating traffic controls.
4) Motorcycle's signal may not be real. Turning signals on a motorcycle usually are not self-canceling, thus some riders, (especially beginners) sometimes forget to turn them off after a turn or lane change.
5) Motorcycles are generally cheaper than other vehicles, therefore, most of the motorcycles do not install navigation systems, though they do have DGPS systems.
6) More stopping distance should be provided for motorcycles. Generally speaking, stopping distance for motorcycles is nearly the same as the one of cars, but slippery pavement makes quick stopping difficult. Also carrying a passenger complicates a motorcyclist's task. Balance is more difficult.

In VTS, user can specify all motorcycles' physical characteristics in Vehicle Characteristic Input module according to their need.

C. Scenario Input

Scenario input includes the data of the intersection type which characterizes the intersection behavior and the type of the collisions. The intersection type has two main parameters. The first one specifies the number of legs at the intersection and second one specifies whether the intersection is signalized or not.

D. Intersection Collision Simulator

The Intersection Collision Simulator is implemented as a modular simulation system with an objected flavor, which is made up of three elements: 1) road, 2) vehicle management and 3) traffic light management.

1) Road: The road module includes the part of the program related to the physical information about the intersection, such as number of lanes and speed limit. The intersection is represented with position data using line segments and arcs. In the simulator, the width of every lane is 3.66 m (12 feet) and the number of lanes in each leg is specified by the user.

2) Vehicle Management: The operation of vehicle management is illustrated in Figure 3. For each vehicle, a set of functions are defined in the vehicle management to simulate their activity. Every vehicle in the simulator is equipped with

- DGPS which offers the exact real-time position data,
- Forward-looking ranging device that can detect the distance to the closest vehicle ahead,

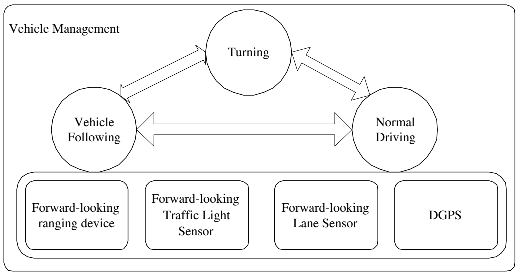


Fig. 3. Operation of Vehicle Management

- Forward-looking traffic light sensor which can detect the color of traffic light at the intersection,
- Forward-looking lane sensor,
- Navigation System which offers digital map and tells location of the intersection(except motorcycles).

a) Vehicle Dynamics: The model of vehicle dynamics is a highly idealized model of all vehicle behavior under successful velocity control and normal road driving conditions. Therefore, the longitudinal model of the vehicle is taken as a unity gain first order linear system with a time constant of 10 msec coupled with acceleration limits of 0.2 g m/sec and deceleration limits (braking limit) of 0.31g m/sec [9], [12]. The acceleration limits are hard limits. The deceleration limits are the same as braking limits, which are determined by coefficient of skidding friction and physical constraint [4]. A general equation for the braking distance can therefore be written as:

$$D_b = \frac{u^2}{30(f \pm G)} \tag{2}$$

where u is the velocity, f is the coefficient of friction and G is the grade of the incline. For zero grade, the deceleration limits will be:

$$a_{decel} = g \times f = 0.31g \tag{3}$$

b) Normal driving: With no vehicle and no traffic light warning ahead, the vehicle attains the normal driving with desired velocity.

c) Car following: When the preceding vehicle is a slower vehicle, the vehicle will be decelerated to come to a specified following distance (primarily safety distance) and match with the speed of the preceding vehicle. When the preceding vehicle is a faster one, the vehicle will be accelerated to achieve the same speed within the acceleration limits. When the vehicle is approaching a signalized intersection with a red traffic light on, the vehicle speed will be decelerated to zero at a specified distance to the intersection.

d) Turning: When the vehicle decides to make a left/right turn at the intersection, it will change to the corresponding lane first. For example, for a four lane road, to make a right turn, the vehicle will move to the rightmost lane when entering the intersection area. Turn trace for the vehicle will be an arc with the following longitudinal and lateral vehicle model:

$$\begin{aligned} \dot{x} &= v sin\psi \\ \dot{y} &= v cos\psi \end{aligned} \tag{4}$$

where v is the current speed, ψ is the yaw angle, and x and y are the current vehicle position in the absolute ground reference frame.

3) Traffic Light Management: The traffic light management module is specially designed for the signalized intersections. Traffic light has two phases only, under this feature, right-turning vehicle will neglect red light traffic signal. For a left-turning vehicle, if it is the first one at the intersection and in the beginning of a new phase, it will yield to opposing vehicles, since no other vehicle will block its sight under such condition.

E. Scenario Input Module

In this module, users can specify the intersection collision scenario for simulation. In this study, we simulate the following representative scenarios:

- Four-leg Signalized Intersection (Left-turning Collision),
- Four-leg unsignalized Intersection (Left-turning Collision),
- Four-leg Signalized Intersection (Right-turning Collision),
- Four-leg Unsignalized Intersection (Right-angle Collision),
- Four-leg Unsignalized Intersection (Right-turning Collision).

For example, Four-leg Signalized Intersection (Left-turning Collision) as shown in figure 4.The green light is on for the north-south direction. Vehicle 1 (Red) is a small vehicle running from north to south while Vehicle 3 (Blue) is another small vehicle which intends to make a left-turn from south to west. Due to the big size of Vehicle 2 (Black), Vehicle 3 does not see Vehicle 1 when it starts to make a left turn. It avoids Vehicle 2 as it plans to, but collides with Vehicle 3 unfortunately.

III. Shadowing Effect

It is a likely scenario that there exist vehicles between the communicating pair and the communication signal are blocked. The possibility being blocked is even high for small vehicles. To simulate the blockage, shadowing effect in inter-vehicle communicationis is implemented in VTS. With limited receiver sensitivity, the shadowing effect will result in path loss, hence a reduced effective communication range.

To study the shadowing effect in IVC, the position of two vehicles mass points are used to set up a rectangular area. For Example: At time T, if the transmitter vehicle is at (x'_1, y'_1) and the receiver vehicle is at (x'_2, y'_2), the shadow area can be created as the rectangle ABCD with corner

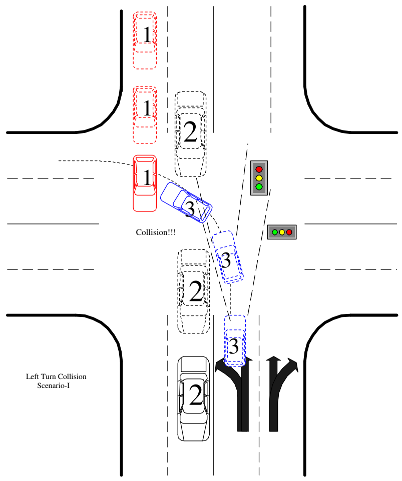


Fig. 4. Four-leg Signalized Intersection (Left-turning Collision)

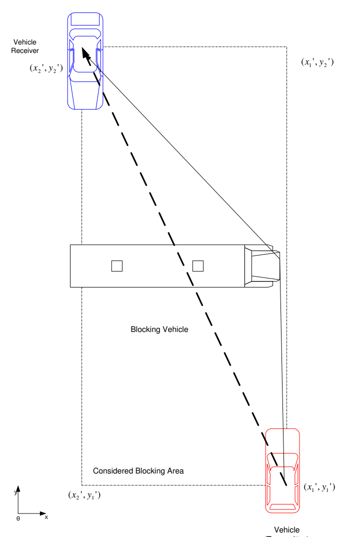


Fig. 5. Receiver in the Shadow

coordinates of (x_1', y_1'), (x_1', y_2'), (x_2', y_1'), (x_2', y_2'), as shown in Figure 5.

Using IEEE 802:11x, the frequencies are in the range of 2.4 -5.925GHz and the corresponding wave length λ is between 0.125m and 0.0506m. Since the carrier wavelength used is smaller than the vehicles sizes (listed in Table I), the diffraction of the communication signal will occur if there exists other vehicle in the shadow area. As shown in figure 6(a), the difference in path length (excess path length) can be computed as [13], [18]

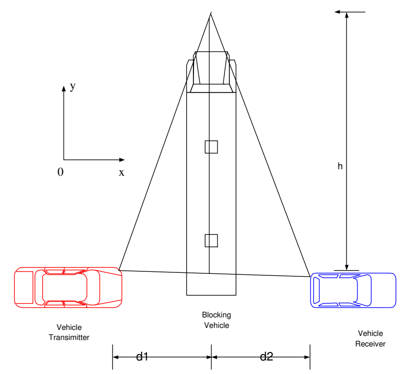
$$\Delta \approx \frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2} \tag{5}$$

where d_1, d_2, h can be computed from following equation as illustrated in figure 6(b), with the position data provided in table II.

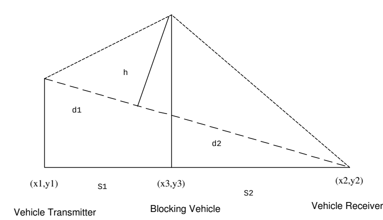
TABLE I

VEHICLES PARAMETERS

	Width(m)	Length(m)
Passenger Car	2.13	5.79
Single-unit Truck	2.59	9.14
Single-unit Bus	2.59	12.19
Motorcycle	0.76	2.13



(a) Path Difference Computation



(b) Parameters Computation

Fig. 6. Computation for Shadowing Effect

$$\begin{aligned} s_1 &= \sqrt{(x_1-x_3)^2+(y_1-y_3)^2} \\ s_2 &= \sqrt{(x_2-x_3)^2+(y_2-y_3)^2} \\ d_2 &= s_2\cos(\arctan(\tfrac{|h_t-h_r|}{s_1+s_2})) \\ d_1 &= \sqrt{(s_1+s_2)^2+(h_t-h_r)^2}-d_2 \\ h &= h_b-h_r-(h_t-h_r)\tfrac{d_2}{d_1+d_2} \end{aligned} \tag{6}$$

Therefore Phase difference will be:

$$\phi = \frac{2\pi\Delta}{\lambda} = \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2} \tag{7}$$

TABLE II

VEHICLES POSITION DATA

	Position	Length
Vehicle (Transmitter)	(x_1, y_1)	h_t
Vehicle (Receiver)	(x_2, y_2)	h_r
Vehicle (Blocking)	(x_3, y_3)	h_b

Fresnel-Kirchoff diffraction parameter:

$$\gamma = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} \tag{8}$$

Using the Fresnel Integral [13], [18], for receivers in the shadow area(diffraction area), the diffraction gain can be expressed as in (dB):

$$G_d = \begin{cases} 0 & \gamma \leq -1 \\ 20\log_{10}(0.5-0.62\gamma) & -1 \leq \gamma \leq 0 \\ 20\log_{10}(0.5e^{-0.95}\gamma) & 0 \leq \gamma \leq 1 \\ 20\log_{10}(0.4-\sqrt{0.1184-(0.38-0.1\gamma)^2}) & 1 \leq \gamma \leq 2.4 \\ 20\log_{10}(0.225/\gamma) & \gamma > 2.4 \end{cases} \tag{9}$$

In order to characterize the shadow gain between every 2 vehicles, an adjacency matrix is defined as following:

$$\varepsilon = \begin{pmatrix} 0 & \varepsilon_{12} & \varepsilon_{13} & \cdots & \cdots \\ \varepsilon_{12} & 0 & \ldots & \cdots & \cdots \\ \varepsilon_{13} & \cdots & 0 & \cdots & \cdots \\ \vdots & \ldots & \ldots & 0 & \cdots \\ \cdots & \cdots & \cdots & \cdots & 0 \end{pmatrix} \tag{10}$$

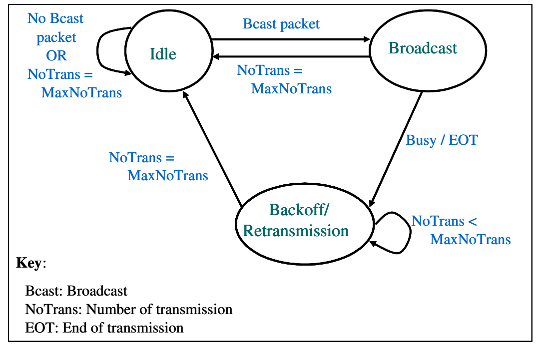
where,ε_{ij} shows the diffraction gain (in dB)for receiver j from transmitter i. This is a symmetric matrix. Note that both negative and positive gain are possible.

IV. The Wireless Simulator

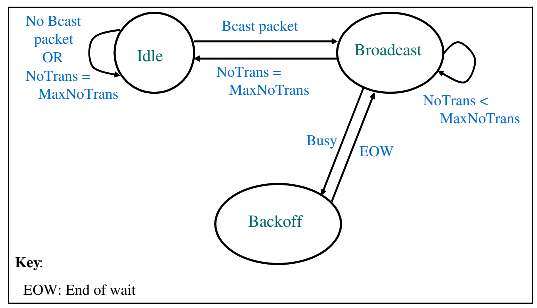
The Wireless Simulator (WS) is an event driven simulator program, which controls the system at discrete time instants. It is based on a simulation library CSIM [17]. The WS models the MAC layer and the PHY layer of the wireless network. In the current version of the simulator, two MAC layer types and two physical layer types exist. Each of them is coded as a separate C file and users select the files according to the desired simulation scenario.

A. Implemented Protocols

1) 802.11x: [3] and DOLPHIN [15] broadcast mechanisms are implemented in the simulator. Note that 802.11x refers to 802.11a, 802.11b, and 802.11a R/A. MAC layer of 802.11x is based on the carrier sense multiple access / collision avoidance (CSMA/CA) mechanism where no RTS-CTS handshake is used and the exponential back off scheme is followed for the retransmissions of the packets.State diagram of the implemented 802.11 broadcast protocol is shown in Figure 7(a). Initially the protocol stays in the idle state until a broadcast packet is generated from the upper layer. Once there is a broadcast packet in the transmission queue, state jumps to the Broadcast. In this state, node senses the channel; if it is free for DIFS time, node broadcasts its packet and state jumps to the Backoff/Retranmission if the maximum number of transmissions is not 1. On the other hand, if the node detects a carrier during this interval, state jumps to the Backoff/Retranmission without broadcasting the packet. State



(a) State Diagram of 802.11 CSMA/CA



(b) State Diagram of Dolphin

Fig. 7. State Diagram of 802.11 and Dolphin

stays in the Backoff/Retranmission until the number of retransmissions is equal to the specified maximum number of transmissions. When a node first enters this state, it sets its back-off timer randomly and starts to decrease it after it finds the channel idle for DIFS time.

2) DOLPHIN: [15] In Dolphin, time is divided into slots and each vehicle can transmit one packet in each slot according to a non-persistent CSMA mechanism. The state diagram of the protocol is shown in Figure 7(b)

When the MAC layer receives a new packet from the upper layers, node checks if it has sent any other packet in the current slot. If it has sent another packet before, node waits for the new slot. When the MAC layer senses the channel busy, it jumps to the Backoff state and waits a random amount of time before jumping to the Broadcast state

B. Physical Layer Modeling

As specified above, there are two options for the physical layer: an ideal physical layer which is error free or a more realistic physical layer with errors. In the latter one, a Large Scale Propagation Model [11] is used to calculate the signal strength at a given distance where received signal strength at a given distance is affected by the transmitter power, path loss and shadowing due to obstacles in the path of the radio signal.

The path loss is one of the mechanisms causing attenuation between the transmitter and the receiver. Several deterministic factors like antenna heights, antenna gains and transmission frequency affect the path loss as well as distance. In addition to these deterministic factors, there is a random factor known as the path loss exponent (n). Received signal power is proportional to the distance raised to this path loss exponent which varies between 3 and 5 in the urban environment. In this presented simulator, n is chosen randomly from this range and path loss including shadowing is calculated as follows:

$$PL(dB) = 10\log 10\left(\frac{G_t G_r (h_t)^2 (h_r)^2}{(d_0)^n}\right)^{-1} + 10\log 10\left(\frac{d}{d_0}\right)^n + \psi_{dB} \tag{11}$$

where d: distance between the transmitter and receiver, n: path loss exponent, d_0: reference distance, G_t, G_r: transmitter and receiver antenna gains, h_t, h_r: transmitter and receiver antenna heights.

By substituting ψ_{dB}, the shadowing effect is included.

C. Fading

After computing the received signal power, the SNRT model [14] together with a specific fading model are used to decide if the packet is successfully received.

Rapid fluctuations of the signal strength can be due to the multipath propagation, the speed of the mobile, the speed of the surrounding objects or the transmission bandwidth of the signal. The Gilbert-Elliot Markov Model is used to model the noisy communication channel in close spatial proximity to a particular location over a short period of time. An one in its output indicates that one bit was transmitted with error while a zero indicates that the bit transmission was successful.

V. Simulations

The simulator was run for 20 vehicles, which are composed of cars, buses, trucks and motorcycles. Cars, buses and trucks have GPS receivers and digital maps. Motorcycles do not have digital maps and they rely on other transmissions in order to locate the position of an intersection. The simulator was run 25 times for the following scenarios: four-leg unsignalized intersection collision scenarios of left turning, right turning, and right angle and the four-leg signalized intersection collision scenario of left turning. In each scenario, vehicles broadcast their 64 byte packets 50 meters away from the intersection. If the vehicle is a motorcycle, even if it is inside the 50-meter zone, it waits for a transmission in order to locate the intersection.

Based on the simulations, for each collision scenario, the packet success rate is computed for 802.11x and Dolphin MAC layers on top of the physical layer with errors operating at different data rates. Then, it is observed that under the current broadcast mechanism and traffic load the packet collisions are unlikely. This is because vehicles transmit their packets when they are 50 meter away from the intersection and for a collision, more than one vehicle should cross the 50 meter border at the same time instant in real life. Furthermore, all of the packet losses were due to physical layer errors. To decrease the packet loss rate, lower data rates may be used in all protocols.

VI. Conclusion

In this paper, a simulator is introduced for simulating both the vehicle traffic at intersections and the wireless communication network between vehicles. Some aspects of the models used are presented. An intersection collision warning system is designed and evaluated by this simulator. It is concluded that the proposed collision warning system is useful for reducing the number of collisions at the intersection. Under a realistic traffic condition, packet losses are mostly due to physical layer errors. As a result, several retransmissions of short packets with a low data rate can improve the success rate of an intersection warning system. The simulator is still under developed.

VII. Acknowledgment

The project is funded by OKI Electric Industry Co. Ltd.

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