Rural Expressway Intersection Surveillance for an Intersection Decision Support System

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ABSTRACT

More than 30% of all vehicle crashes in the US occur at intersections; these crashes result in nearly 9000 annual fatalities, or approximately 25% of all traffic fatalities. Moreover, these crashes lead to approximately 1.5 M injuries/year, accounting for approximately 50% of all traffic injuries. In rural Minnesota, approximately one-third of all crashes occur at intersections.

AASHTO recognized the significance of rural intersection crashes in its 1998 Strategic Highway Safety Plan, and identified the development and use of new technologies as a key initiative to address the problem of intersection crashes.

A study of 3,700 rural Minnesota intersections showed that right angle crashes account for 36 percent of all rural intersection crashes. Approximately 50 percent of the crashes at intersections having higher than expected crash rates are right angle crashes. Further investigation also found that poor gap selection is the predominant causal factor in these intersection crashes.

To address this problem of poor gap selection, the University of Minnesota and the Minnesota Department of Transportation (Mn/DOT) have, under development, a rural Intersection Decision Support (IDS) System which, when deployed, will provide a driver additional information needed to make correct decisions regarding the available gap.

Described herein is the surveillance component of a rural IDS system. The surveillance system uses sensors, processors, and a communication system to determine the intersection “state” including location, speed, acceleration, lane of travel, and vehicle classification (where necessary) of each vehicle within the surveillance zone. This state information will determine when to activate alerts and warnings.

INTRODUCTION

Motivation

More than 30% of all vehicle crashes in the US occur at intersections; these crashes result in nearly 9000 annual fatalities, or approximately 25% of all traffic fatalities. Moreover, these crashes lead to approximately 1.5 M injuries/year, accounting for approximately 50% of all traffic injuries.

In rural Minnesota, approximately one-third of all crashes occur at intersections. AASHTO recognized the significance of rural intersection crashes in its 1998 Strategic Highway Safety Plan (1), and identified the development and use of new technologies as a key initiative to address the problem of intersection crashes in (2), Objective 17.1.4: “Assist drivers in judging gap sizes at Unsignalized Intersections.”

To clearly define the rural intersection crash problem, an extensive review of both the Minnesota Crash Database and research reports quantifying the national problem was undertaken; the results are documented in (3). This study of 3,700 Minnesota intersections shows that crashes at rural expressway thru-STOP intersections have similar crash and severity rates when compared to all rural thru-STOP intersections. However, right angle crashes (which are most often related to gap selection) were observed to account for 36 percent of all crashes at the rural expressway intersections. At rural expressway intersections that have higher than expected crash rates, approximately 50 percent of the crashes are right angle crashes. Further investigation also found that drivers’ inability to recognize the intersection, and consequently run the STOP sign, was cause for only a small fraction of right angle crashes. Gap selection is the predominant problem.

1. The driver looked but did not see the other vehicle (62.1 %)
2. The driver misjudged the gap size or velocity of the approaching vehicles (19.6 %),
3. The driver had an obstructed view (14.0 %), or
4. The roads were ice-covered (4.4 %).

Of these four driver errors, the first three can be described as either problems with gap detection or gap selection.
Recent crash analyses, including field visits and crash database reviews, for Michigan (5), North Carolina (6), and Wisconsin (7) have shown that in these states, poor gap acceptance on the part of the driver is the primary causal factor in approximately 60% of rural thru-Stop, right-angle intersection crashes.

**Design Premise**

Given the extent of the crash problem and the causal factors, an IDS system design has developed based on the following design factors:

1. In the majority of the rural thru-Stop crashes, the driver has obeyed the stop sign. This implies that the driver is cognizant of his/her situation, and that it is likely that the driver interface used at the intersection is likely to capture the driver’s attention. This is a significant departure from the signal/stop sign violation problem, where the intervention system has to both capture the driver’s attention and convey a timely message with substantial authority that a violation is imminent if a proper response is not executed.

2. With the premise that the driver’s attention has been captured, the IDS system will provide a driver timely, relevant information regarding unsafe conditions. The purpose of the system is to provide this information as a means to enable a driver to make a safer decision regarding gap acceptance, but not make the decision for the driver. A prohibitive reference frame (i.e., telling a driver when not to go) is used to lessen liability issues with indicating to a driver when it is safe to go.

3. Given the increasing traffic volumes on rural expressways and the need of traffic engineers to maintain or increase capacity on these roads, the IDS system should not stop traffic on the main road. The IDS system should provide some of the safety benefits of a signal-controlled intersection without the adverse effects on mainline capacity, throughput, and congestion.

**Problem Solution**

With sponsorship from the Infrastructure Consortium Intersection Decision Support (IDS) project, Minnesota DOT (Mn/DOT) and the University of Minnesota are developing a technology-based approach to solving the gap acceptance problem for rural intersections. This rural IDS system is designed to provide a driver the information needed to make correct decisions regarding the available gap. The system is designed to provide some of the safety benefits of a signalized intersection (fewer crashes, opportunities for all drivers to enter/cross the traffic stream, etc.) while minimizing the downsides (expense of installation, disruption of traffic flow, etc.). It should be noted, however, that the IDS system will not provide additional opportunities for drivers to enter/cross the traffic stream because unlike a traffic signal, it will not create gaps that were not already there.

The IDS system consists of two primary subsystems: the surveillance subsystem, and the driver interface subsystem. The surveillance system is described in the sequel; the driver interface is described in (8).

The surveillance system uses sensors, computer processors, a communication network, and a geometric representation of the roadways to determine the “state” of the intersection. Mainline state information includes the position, speed, (derived) acceleration, and lane of travel of each vehicle within the surveillance zone. This state information, combined with known intersection geometry, facilitates the real time tracking of traffic gaps on the mainline. Minor road state information includes the position and speed of the vehicle on the minor road, and an estimate of the classification of the vehicle. Present classification separates vehicles into four categories: Motorcycle/passenger cars, SUV/light truck, medium duty truck/school bus, and heavy-duty truck/semi/motor coach/farm equipment. A central processor computes the “state” of the intersection at 10 Hz.

The state information provides the basis with which to assess threats to drivers waiting to cross or enter the mainline traffic stream. In addition to intersection state data, the threat assessment algorithms may utilize parameters including driver demographic information (potentially available wirelessly), road condition information (from weather/road sensors mounted at or near the intersection), and vehicle information (model, performance parameters, etc., potentially available wirelessly).
The IDS system is designed so that should an unsafe condition be detected by the threat assessment algorithm, the central processor initiates the proper warning to the driver through an infrastructure-based interface known as the Driver-Infrastructure Interface, or DII. The design of the DII has not yet been finalized; work continues to finalize a design acceptable to state DOTs and the National Committee on Uniform Traffic Control Devices.

Prototype System

As a means to develop and validate a rural intersection surveillance system, a prototype rural IDS surveillance system has been designed and built at the intersection of US 52 and County State Aid Highway 9 in Goodhue County, MN. Although this prototype intersection instrumentation represents a single instance of this technology, its design is flexible and extensible to any rural intersection. In fact, the authors are presently developing a portable intersection surveillance system which will be taken to a variety of states in the US, and used to collect driver behavior at select rural intersections where crash rates are higher than expected. This data will be used in the development of the driver interface to produce a ubiquitous system capable of functioning anywhere in the US.

The surveillance system required for deployment of a rural IDS system is a subset of the system described herein. The system described below has been designed to capture driver behavior in order to determine factors leading to poor gap decisions (i.e., mainline traffic conditions, weather, time of day, etc.), and as such, provides surveillance of the mainline, the minor approach, and the median crossroads, where the median crossroads is defined as the paved area where the minor road crosses the mainline median. The rural IDS system, when deployed, requires only mainline and minor approach surveillance.

Median crossroad surveillance is used to monitor critical driver behavior. Crash statistics indicate that more than 80% of intersection crashes at median separated rural intersections occur on the “far” side of the intersection. A prevailing hypothesis assumes that once drivers reach the median, they feel compelled to travel onward rather than stopping and re-evaluating the present situation, leading to the crash on the far side of the intersection. Data collected in the median will be used to substantiate or refute this hypothesis.

A plan view of the prototype intersection surveillance system is shown in FIGURE 1 below. Mainline sensing is provided by an array of radar sensor spaced 400 ft (122m) apart, and connected to a central processor through a hardwire local area network. Minor road sensing is provided by a fusion of radar and scanning lidar, also connected to a central processor through a hardwire local area network. A machine vision-based system, using both visible and infrared light cameras, is used to provide surveillance for the median crossroads.

One underlying objective of the IDS program is to develop an effective, deployable system. Because of tight budgetary constraints, the system to be deployed must exhibit high performance:cost ratios. The cost goal of the IDS system is to be competitive with the cost of a four way signal controlled intersection. In Minnesota, a four-way signal controlled intersection costs approximately is $250,000.

MAINLINE SURVEILLANCE SYSTEM

Requirements and Constraints.

The main performance requirements include a minimum of 20 seconds (at the 85% percentile speed of the mainline) of continuous sensor coverage, an object detection rate in excess of 99.99%, and the estimated time to intersection of each vehicle tracked by the mainline sensor system should be accurate to 250 msec or better. Mn/DOT construction constraints stipulate that

- no sensor can be located closer than 12 ft (3.66 m) to the roadway,
- any device within 30 feet of the roadway be powered with a direct current source of 15 volts or less,
- all fixtures must meet state and federal breakaway standards
- all electrical equipment located in the clear zone must be equipped with breakaway electrical connectors
- no equipment shall be located in the median of the expressway.
FIGURE 1. Plan view of a rural intersection surveillance system. Of particular interest for driver behavior research is the crossroad surveillance area. 80% of crashes on rural expressways occur on the “far” side of the intersection. Understanding of behavior in the median will facilitate the development of an effective driver interface.

Sensors
Radar has been used in many traffic engineering applications. Functional requirements specify that the surveillance system provide lane of travel information for the vehicles detected by the surveillance system. Radar designed for traffic monitoring use very narrow horizontal fields of view (width of sending cone is less than one lane width at maximum range), and are typically mounted on overhead gantries, with one sensor per lane. Because of the lack of available overhead structures on which conventional traffic radar can be mounted at rural intersections, their applicability was discounted.

However, new generation automotive radar can provide range, range rate, and azimuth angle to multiple targets (up to 8 targets). *A priori* knowledge of the road geometry combined with the sensing capability allows the sensor to provide the information needed to meet system requirements. Automotive radar was a clear choice because of its wide field of view.

Three automotive radar were evaluated to determine an optimal sensor for this application: Autocruise LR, Delphi ACC 3, and Eaton-Vorad EVT 300. The EVT was selected based on its performance:price ratio (9). The claimed performance specifications of the EVT-300 follows:

- Operating frequency: 24.5 GHz
- Maximum Range: 350ft (107m)
- Range rate: 0.5 to 100 mph (0.8 to 162 kph)
The EVT-300 was subject to an extensive performance evaluation in the context of a roadside sensor (10), where the performance claims of the EVT-300 were found to be conservative, especially maximum range, which was found to be approximately 440ft (134m). Moreover, the EVT-300 utilizes a carrier frequency of 24.5GHz, which is less sensitive to signal attenuation due to atmospheric moisture than other radar which use a carrier frequency of 76 GHz (11). Both the Autocruise and the Delphi use a 76 GHz carrier frequency.

**Sensor Layout.**

The layout of sensors on the test intersection is shown in FIGURE 2.

![FIGURE 2. Mainline sensor configuration for rural intersection surveillance system. Hardwired communications from the sensors to the central computer are used for permanent installations whereas wireless communication is used for portable installations.](image-url)

Radar sensors R1-R5 and R8-R12 represent sensors which will be used in a deployed IDS system; sensors R6-R7 and R13-R14 are used to collect driver behavior data, and represent a research component. Sensors R6-R7 and R12-R14 are used to determine acceleration data for drivers entering the traffic stream as well as to determine the response of mainline traffic should a driver accept too small a gap and create a conflict with the mainline. The response of the mainline traffic would be deceleration, appropriate lane changing, or retaliation (i.e., rapidly...
approaching the entering vehicle to “teach them a lesson”); mainline traffic response will be used to determine optimal alert and warning timing.

To accommodate clear zone requirements, only the radar sensor is mounted near the roadside. The local processor and communication equipment is located out of the clear zone, a minimum of 35 feet (10.7m) from the road surface. FIGURE 3 below illustrates the system as deployed at the test intersection.

![FIGURE 3. View of Radar Sensor station as deployed on US 52. Sensor is located no closer than 12 feet (3.6 m) to road surface. Local processor, power, and communication are located no closer than 35 feet (10.7m) to road surface.]

**Data Flow.**

The surveillance system architecture represents a hybrid between localized and distributed processing. FIGURE 4 below presents a high level dataflow diagram of the mainline sensor process.

Each radar station has its own processor. The processor provides three functions. First, radar data is provided with a time stamp provided by a local NTP (Network Time Protocol) signal synchronized with an NTP server at the main controller cabinet. This allows the 14 remote radar sensors to reference a single time standard. Second, radar data is transformed to the global coordinate frame from its local coordinate frame. Third, global radar data is processed using local geometric data to determine which detected targets are on the roadway or shoulder. Targets not on the roadway or shoulder are discarded, and the filtered target list is collected and sent to the central processor.

The central processor collects mainline sensor data for 14 sensors. Because the sensors operate asynchronously, radar data must be aligned temporally before the mainline state can be computed. All radar data is projected ahead to a specific fixed time, using previous intersection state data and newly arriving radar sensor data. From the radar projection, a new mainline state is calculated. This process is repeated at 10 Hz, providing a new mainline state vector every 0.1 second. More details regarding the state estimation process, including the technique used to identify new targets and to discard old ones, are provided in (12).

**Performance results.**

The mainline surveillance system was tested and validated in three performance categories: detection rate, tracking accuracy, and masking.

**Detection Rate.**

The EVT-300 sensors are automotive sensors, designed to be mounted in the center of the vehicle such that the main sensor beam is aligned with the vehicle longitudinal axis. In this application, the sensor is mounted 12 feet (3.6 m) from the side of the road so that cars approaching the sensor are located off of the main axis. Prudence dictates that it is necessary to test that the sensor does sense all approaching vehicles.
FIGURE 4. High-level data flow for mainline sensor data. Local radar processor performs coordinate transform and target/database matching to assign a lane of travel. Once pre-processing is complete, data is time stamped and sent to the main controller. At the main controller, incoming data from all radar sensors are temporally aligned, facilitating a best estimate of the position, speed, lane of travel, and time to crossroads for each vehicle on the mainline.

Three sensors were used in the evaluation: the EVT-300, a retro-reflective laser sensors, and a video-capture camera. Three sensors were used so that discrepancies between sensors could be identified, and traced back to determine which sensor indicated either a missed or “phantom” target. (A phantom target is one not physically present, but detected by the sensor.)

The experimental set configuration is shown in FIGURE 5. A search area of 35m after the location of the laser beam was utilized. This search area accounts for any position errors, and signal acquisition and transmission lags between the retro-reflective controller computer and the image-capturing computer. Data collected over a three-day period indicated 51,942 laser scanner crossings and 51,934 radar detections. Reviewing captured video, seven radar “misses” were due to false triggering of the retro-reflective sensors, likely caused by flying debris. With just the one miss, the vehicle detection rate of the system is 99.998%.

It is important to note that this experiment was carried out for a single radar station. Multiple sensor stations decrease the likelihood that a particular vehicle could pass along the mainline without detection by at least one sensor.
FIGURE 5. Experimental configuration for radar detection rate verification. Search zone encompasses both radar and camera fields of view.

Tracking Accuracy.

Tests were conducted to determine the accuracy of the mainline system in terms of vehicle speed and position in a lane. Differential GPS (DGPS), accurate to 15.4 cm (6 in) at 1 standard deviation \(^{(13)}\) was used as a measurement reference with which to judge the radar-based mainline state estimation system. DGPS corrections were broadcast from the intersection main controller. A sedan and a truck, each equipped with this DGPS system, served as probe vehicles. This mix facilitated quantification of the differences in accuracy for the two vehicle types.

The probe vehicles were driven along the mainline, varying speed and lane of travel over multiple runs. The in-vehicle systems were synchronized with the main system controller using NTP over a wireless 802.11b network. The longitudinal time error (secs), longitudinal position error (meters), lateral position error (meters) and speed error (m/s) were calculated for each GPS position recorded during testing.

The mean longitudinal time error for all the runs was found to be -0.107s with a standard deviation of 0.096s. Moreover, longitudinal time errors are usually less than 0.25s. The longitudinal time error directly affects the measurement accuracy of gaps and hence, the worst-case error in gaps caused by longitudinal position error would be 0.25s.

The mean longitudinal lane position error for all the runs was found to be -10 ft (-3.07m) with a standard deviation of 2.72m (8.9 ft); 95.5% of the data was within two standard deviations (-28 ft to 8 ft (-8.5m to 2.4m)). The truck exhibited larger longitudinal position errors than the sedan. This is due to the ambiguity of the detection region of the radar on the vehicle; see \(^{(14)}\) which documents the performance of the EVT-300 radar as a traffic sensor.

The ability to track vehicle laterally, i.e., assign the proper lane of travel, was also documented. For a target to be correctly placed in the proper lane, this error should be less than 4 ft (1.2m). The mean lateral error for all the runs was found to be -0.4 ft (-0.122m) with a standard deviation of 2.5 ft (0.76m). To ensure that lane changes are not falsely detected, the vehicle-tracking module does not confirm a lane change until the target is well into the new lane.

The speed accuracy for the mainline system is better than 0.73 mph (0.33 m/s) RMS when the vehicle is in the field of view of a radar sensor. Accuracy may degrade significantly should a masked vehicle accelerate or decelerate at a high rate. However, this inaccuracy will not be sustained because hard acceleration or deceleration will “unmask” the hidden vehicle, at which point its range and range rate will be measured accurately once it enters the field of view of the radar sensor.
“Masking” effects.

Because of DOT constraints regarding the placement of sensors, masking of targets is likely to occur. Masking occurs when the signal from the radar sensor is unable to hit all targets because another target blocks the path of the sensor signal. Masking occurs either laterally or longitudinally, and is shown in FIGURE 6.

![FIGURE 6. Examples of masking of radar targets. Lateral masking is found on the left, with the green target blocking the purple, dotted target. Masking is illustrated on the right, where the purple target is masked by the green target because it follows too closely.](image)

Masking can affect the mainline state estimation process, but its effects are rather small. Accuracy will degrade to no worse than 75ft (23m) (the maximum length of a semi-tractor trailer in Minnesota) should a vehicle be masked laterally. It is important to note, however, that masking will not degrade the performance of the IDS system as gaps are defined in terms of both lanes, and not a left lane gap and a right lane gap. If speed differentials for left and right vehicles are high, a vehicle will be masked only for a short period of time before it becomes visible to the mainline sensors. Once the vehicle is detected, its threat level can again be accurately assessed.

Testing using DGPS equipped probe vehicles shows that if vehicles are separated longitudinally by more than 53ft (16m), the radar will detect and track 99% (at one standard deviation) both vehicles. The vehicle closer to the intersection will be detected at the 99.977% rate described above. This does not adversely affect the performance of the IDS system.

Motorcycles are also addressed. Motorcycles have relatively small radar cross sections when compared to large vehicles. An experiment was performed to determine at what separation distance a motorcycle is masked in the radar cross section of a truck. This experiment was carried out using a Suzuki Bandit 1200 motorcycle and an International 2540 crew-cab snowplow. The radar could reliably distinguish the motorcycle from the truck radar cross section as long as the motorcycle led the truck by 43 feet (13.0 m). At 55 mph (24.5 m/s), this is a headway of 0.5 sec. This is clearly sufficient for this application.

MINOR ROAD SURVEILLANCE

Minor road surveillance serves three purposes. First, it detects the presence of a vehicle waiting to enter the traffic stream. To minimize distraction to the mainline traffic, a DII would only be activated in the presence of a vehicle on the minor road. Second, minor road surveillance system estimates vehicle classification. It is expected that larger vehicle require more time to cross or enter the traffic stream than do smaller vehicles. To assure user acceptance, warnings and alerts must be timed appropriately; proper timing is a function of vehicle class. Third, the minor road surveillance system may be used as a means to prevent unintended stop sign running. The minor road surveillance system measures range and range rate to the stop bar; should a driver approach the intersection with a trajectory indicating a stop sign run, the sensor can “fire” the DII with the goal of catching his/her attention. This added functionality comes as a zero-cost option to the IDS system.

The sensor station layout is similar to that for the mainline. Roadside sensors can be provided with only DC power of less than 15 volts, and a sensor can be located no closer than 12 feet (3.6m) to the road surface. Therefore, each sensor is connected to a data processing computer in a separate cabinet. This cabinet is located outside the Mn/DOT specified clear zone at least 30ft (9.1m) from the road shoulder.

A three sensor suite is used for vehicle classification; two scanning lidar sensors, and an EVT-300 radar sensor. An EVT-300 is used to sense vehicles approaching the intersection on the minor roads. A horizontally
placed lidar detects slow moving and stopped vehicles approaching and located at the stop bar, and is used to estimate vehicle length. A vertically placed lidar is used to capture the height profile of the vehicle as it passes by. FIGURE 7 shows how the vertical and horizontal lidar data is used to compute a “snapshot” of the side profile of a vehicle.

- Group 1: Motorcycles, sedans and small SUVs (Class 1 and 2),
- Group 2: Large SUVs and pickup trucks (Class 3),
- Group 3: Single-unit trucks (Class 4 – Class 6), and
- Group 4: Semi-trucks and other large vehicles (class 7 and higher)

The classification system was validated by using a three sensor suite consisting of the vertical and horizontal lidar, a retro-reflective laser presence detector, and a video camera/capture board. When a vehicle moved into the field of view of the classification system, the laser scanners produced a vehicle profile, and model matching software assigned a vehicle classification. The retro-reflective sensor triggered the video camera to record an image of the vehicle at the stop bar. Accuracy of the classification system was validated by comparing the classification assignment to the image captured by the video camera, and is shown in TABLE 1 below.

![FIGURE 7. View of horizontal and vertical laser sensors. Horizontal tracks position of the vehicle as it approaches the stop bar and calculates the length of the vehicle. The vertical sensor detects the point of the highest reflection as the vehicle passes by, enabling the estimation of the vehicle side profile. The profile is then assigned to one of five vehicle classes.](image)

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**MEDIAN CROSSROADS SURVEILLANCE.**

Although a deployed IDS system will not require crossroads surveillance, to best understand driver behavior at rural expressway intersections, driver behavior in the crossroads median must be understood. Instrumentation was designed to estimate vehicle trajectories in the crossroads median.
Initial system design used a pair of horizontal lidar sensors to “sweep” the median to detect the presence and location of vehicles in the median. However, Mn/DOT raised concerns regarding the longevity of a sensor because snowplows push significant volumes of snow into that area and signs located in that area are often hit in crashes.

Heeding Mn/DOT’s concern, both visible light and infrared cameras were used to track vehicles in the median; the northeast and southwest corners of the intersection are equipped with one visible light and one IR camera. During daylight hours, visible light cameras are used to track vehicles in the median; IR cameras are used from dusk to daylight. Local sunrise/sunset data is used to determine which camera data is used to track vehicles. Details regarding image processing can be found in (12).

Performance of the median crossroads surveillance system was validated using a DGPS-equipped probe vehicle. Of primary interest is the time of arrival and time of departure of the vehicle entering the median crossroads; the goal of the surveillance system is to determine whether motorists stop in the median and make a deliberate gap acceptance decision, or just drive through. The mean longitudinal time error for all the experimental runs for the straight through maneuver was found to be -0.302s with a standard deviation of 0.046s. These errors are minimal and do not significantly affect the measurement of the gaps selected by vehicles making these maneuvers.

CONCLUSIONS AND FUTURE WORK.

The design and performance of a rural intersection surveillance system has been provided. The system has been designed to operate 24/7 in all weather conditions. The system tracks mainline, minor road approach, and median crossroads vehicle trajectories, and offers vehicle classification on the minor road. This surveillance system will form the basis for a rural Intersection Decision Support System.

Because rural expressway crashes are a national problem, state DOT interest in countermeasures to prevent these crashes is high. Mn/DOT is leading an eight-state pooled fund study (TPF-5(086)) to examine rural expressway and highway crashes. Under this contract, a portable intersection surveillance system is being constructed. This portable system will be brought to problematic intersections identified in each state, and data will be recorded for a period of one month. Data collected at these intersections will be used to determine, on a macroscopic basis, whether regional differences exist in the gap acceptance process. Knowledge of these differences, if they exist, will facilitate the design and deployment of a ubiquitous driver interface usable regardless of geographic location.

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REFERENCES