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Video Based Simulation of Daytime and Nighttime Rain Affecting Driver Visibility

William T. Neale, James Marr, David Hessel, and Robert Gillihan Kineticorp LLC

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Abstract

This paper presents a methodology for generating video realistic computer simulated rain, and the effect rain has on driver visibility. Rain was considered under three different rain rates, light, moderate and heavy, and in nighttime and daytime conditions. The techniques and methodologies presented in this publication rely on techniques of video tracking and projection mapping that have been previous published. Neale et al. [2004, 2016], showed how processes of video tracking can convert two-dimensional image data from video images into three-dimensional scaled computer-generated environments. Further, Neale et al. [2013,2016] demonstrated that video projection mapping, when combined with video tracking, enables the production of video realistic simulated environments, where videographic and photographic baseline footage is combined with three-dimensional computer geometry. This paper augments this existing technology through techniques and methodologies that incorporate the adverse weather condition of rain into the simulated environment. A method for simulating the effect of rain on drivers' visibility is developed by analyzing and modeling actual video footage obtained in both dry and rain conditions, during the day and at night. Baseline, raw video footage that does not contain adverse weather is video tracked, and through projection mapping and the use of modeling that represent rain, this baseline footage is rendered to properly display the effect rain has on driver visibility. The resulting simulation is then compared to calibrated raw video that shows the same area of the roadway but recorded when the adverse weather condition was actually present. In other words, the computer-simulated effect of rain on drivers' visibility is compared to calibrated footage of video driving on the same roadway and under actual rainy weather conditions. The paper demonstrates that through these methodologies, video realistic simulated rain can be created that accurately represent the driver's visibility in adverse weather conditions. When comparing the simulated rain environment to the original video footage that captured baseline rainy condition, the results show that the view from the driver's perspective are rendered the same.

Introduction

Industries ranging from automotive safety and testing, to the gaming and entertainment industries benefit from methodologies that enable the creation of computer generated, video-realistic environments. Not only does the experience of the viewer more closely resemble the actual environment experienced in the real world, the simulated environments allow for flexibility in changing conditions encountered on the road - such as roadway with hazards, other vehicles, or varying weather conditions. In computer simulated environments, these conditions can be changed and adapted to visually represent different driving conditions [1,2]. In the research presented here, the adverse weather condition of rain is explored. Rain was analyzed since it is commonly encountered and may create adverse driving conditions. These adverse conditions may contribute to reduced driver visibility, and the ability to reproduce them in a simulated environment affords the viewer a realistic experience of the condition, without the associated risk, and can be useful in analysis, studies or demonstrations that seek to better understand a driver's vantage point during inclement weather. The methodology in this paper uses video footage taken under typical dry weather conditions, modified through computer visualization to appear as if it was obtained during rainy conditions. This flexibility allows the production of video realistic environments that show specific weather conditions, even if it is not practical or feasible to obtain a live recording of the desired weather condition.

To create video realistic simulated environments of rain, calibrated video footage from the driver's view was first obtained that shows a roadway under both dry and wet footage. This video footage was obtained with high-definition equipment, using accepted calibration techniques, and represents the driver's perspective both during daytime and nighttime conditions, and in varying rates of rainfall [3,4,5,6,7]. A computer-generated environment was built of the same location that the in-field video recordings were captured. The geometry of this computer environment was first rendered using textures and lighting from the in-field video that was obtained at the location under non-adverse conditions.

Analyses were then performed on both the dry and wet in-field video recordings to understand how rain affects the driver's view, and how this effect is manifested in the video imagery. The effect of rain included a change to the surface properties (as water fills in surfaces) and the resulting change in reflectivity. Additionally, particles in the air and on the windshield also contribute to the change in visibility.

After analyzing in-field video imagery and how rain affects a driver's view, computer visualization tools were used to simulate the effect of rain. The computer environment that was built of the location where video recordings were obtained was reprocessed using these tools, such that reflectivity and particles mirrored the effect of rain. The result is a video realistic computer-generated environment showing rain's effect on driver visibility. This computer simulated version was compared to the actual in-field video recording taken during rain conditions. Visual and quantitative comparisons between the simulated video rendering and the original in-field video recording demonstrate that both look essentially the same.

Background

Water particles in the air, and water collecting on the roadway surface can alter the way light is reflected and transmitted to the driver, affecting the driver's visibility. Research on the reduction of driver visibility demonstrates that even in light rain, the visibility of objects in the roadway can be diminished [8], and in moderate to heavy rain the reduction can range from 20-50% [9,10,11]. Visibility can further be affected by the speed of traffic, surrounding light sources, and the rate that windshield wipers are operating [12]. A meta-analysis study from research and reports published between 1970 to 2005 showed a 71% increase in crash rates during rain conditions, demonstrating the adverse effect rainy weather can have on driver operation and visibility [13]. Studying the effects of rain on visibility can help roadway design, vehicle design, and driver education. Research on how rain affects driver visibility has been performed in real world simulations, including studies at the Virginia Smart Road. This 2.2-mile long controlled-access test track is managed by the Virginia Tech Transportation Institute and features a half mile long weather making system which is fed by a 500,000-gallon water tank pumping water to towers mounted on the road's shoulder, producing up to 1.2" of rain per hour. In 2004-2005 the U.S. Department of Transportation conducted extensive rain adverse research along the road to test visual performance during nighttime conditions while driving in rain [14,15]. As an alternative to the real-world simulation, a computer-generated environment can also provide important information about driver visibility, and the effect of rain. An added benefit of the simulation being tied to a computer environment is the flexibility to change specific conditions that need to be analyzed or studied. For instance, the speed of the driver, other vehicles or objects on the roadway, and different driving environments and lighting scenarios. The driving principle behind the method presented in this paper is that a computer simulated environment can be created that is photorealistic, representing light, texture, color and the elements of the environment is a realistic manner. This method uses original non-adverse weather video converted to a three-dimensional environment. The geometry in this computer environment can then be assigned the surface properties from the video itself through projection mapping, such that it looks like the original video, but is entirely three-dimensional. The properties of the geometry in this three-dimensional environment can then be adjusted such that the lighting (reflection, surface texture, and refraction) of the objects can be adjusted to match the video footage that shows the adverse weather.

Procedure and Methodology

Demonstrating and evaluating the methodology described in this paper involved the following list of steps. In general these steps include obtaining baseline in-field video of wet and dry conditions, creating a three-dimensional computer environment of the location, processing the materials and textures from the video into the environment, and then using simulation algorithms to render the geometry and lighting in the computer environment to look like it does in the in-field video taken during rainy weather. The result is a computer-generated video that looks like the original in-field video.

a. Collect video footage of adverse weather on multiple roadway types and during the day and night
b. Collect video footage in same area and during the same time frame but under non-adverse weather conditions
c. Collect 3D geometry of the subject roadway area
d. Use tracking and projection mapping to process the non-adverse footage into a three-dimensional computer environment.
e. Analyze the video to determine how adverse weather footage differs from non-adverse weather footage in terms of those factors that influence visibility such as reflections, lighting, color and particles in the air.
f. Use computer visualization techniques to the simulate in the computer environment, the effect rain has in terms of reflections, textures, lighting, and particles to match what is observable in the original in-field video of a rain condition.
g. Render the composited final video and compare this to the original calibrated weather-affected footage

The final composited computer-generated rendering was compared to the actual recording of the rain condition on the same roadway to evaluate how closely the simulated image matches the actual video recording.

Collecting Video Footage under Adverse Weather Conditions

The first step in this methodology included obtaining video footage, from a driver's perspective, under rainy conditions. Capturing video-realistic imagery, of a specific weather pattern on a specific stretch of roadway, requires a bit of luck, since it is difficult to accurately predict weather patterns. Compounding the problem is that the time it takes to travel to an area that has the desired weather can be long enough for the weather to change by the time of arrival. Fortunately, capturing non-adverse weather in the same area is easier since it is more predictable and more frequent. Thus, adverse weather was the focus for obtaining footage, with the goal of returning to the same location at another time to obtain non-adverse weather. To obtain the highest quality footage, and record a view where the lighting, colors, and values of the recording are representative of the actual scene when viewed live with the naked eye, a Sony A7s HD video camera and Atomos Shogun field monitor were used in conjunction with devices that enable calibration of the video image prior to recording. *Figure 1* shows the equipment used in obtaining footage, including calibration tools. *Figure 2* shows the setup of the camera inside the testing vehicle.

Daytime and nighttime rain footage was obtained using accepted methodologies for calibrating video [16]. Since video footage was obtained under varying rain conditions, each video was categorized into one of three rain fall rates- light, moderate or heavy based on visual observation and by referencing provided weather reports from the closing reporting stations [17]. These categories are defined by a rate of rain fall accordingly: Light (0.0 to 0.1 in/h), Moderate (0.11 - .29 in/h), and Heavy (.30 in/h or more) [18]. Though the rate of rainfall may vary, the general principles that cause reduced visibility in rain are the same, just to a lesser or greater degree depending on the rain fall rate.

FIGURE 1 - Setup of equipment for video recording

FIGURE 2 - Equipment inside the testing vehicle

Collecting Video Footage under Adverse and Non-Adverse Weather Conditions

In addition to collecting video under rain conditions, video from the driver's perspective was also captured in the same location under dry conditions. Using the same methodologies to setup the video equipment and calibrate the cameras, video footage was obtained when there was not any rain, for each of the sites where rain footage had been collected. Video was taken with overcast skies, to eliminate shadows from the sun which would not have been present during any the rain conditions. *Figure 3* and *Figure 4* demonstrate comparable images from two separate video recordings showing adverse weather

FIGURE 3 - Still images from video recording of dry weather

FIGURE 4 - Still images from video recording of light rain

TABLE 1

	Location	Date	Rain Rate	State	Lighting
1	I-25 South	5/3/2017	Moderate	CO	Daytime
2	I-25 South	5/10/2017	Moderate	CO	Nightime
3	HWY 285 WB, mm243	5/10/2017	Light	CO	Daytime
4	MO-AB at Nash Rd	4/25/2019	Light	MO	Daytime
5	HWY3/ Grapview Rd	4/4/2017	Light	WA	Daytime
6	Greenwood Plaza BLVD	10/22/2015	Light	CO	Daytime
7	Stone way at N 41st ST	1/5/2016	Light	WA	Nighttime
8	Sunset HWY at Canyon	11/8/2017	Light	OR	Nighttime
9	Sunset HWY at Canyon	11/8/2017	Light	OR	Daytime
10	New Jersey Turnpike	2/22/2010	Heavy	NJ	Nighttime
11	Arapahoe Rd at Potomac	10/24/2012	Heavy	CO	Nighttime

with rain (Figure 3) and non-adverse clear weather. These were taken during daytime lighting conditions.

A total of 11 sites were accessed and recorded under varying rain conditions. *Table 1* documents the sites, and conditions where video was recorded. Five different states had video collected at roadways from single lane to highway. Between the states, and different roadways, the manner in which rain affects driver visibility was not different, since the principles of rain are the same regardless of which state one is located. However, site specific differences such as the type of roadway, ambient lighting, and the speed the vehicle was traveling can change how the rain, and its effect on visibility, appears in the video recordings.

Three-Dimensional Computer Modeling of the Scene and Lighting

Underlying the methodology in this paper is a previous published method for creating a three-dimensional video realistic computer environment [19]. In this previous paper, video is recorded, and a three-dimensional computer environment created that contains the same geometry as that which is visible in the video, such as the roadway, signs, guardrails, street poles and other roadway objects. By projection mapping the texture, color and material properties of the from the video on to corresponding objects in the computer environment, the computer environment can be viewed such that it looks the same as the video, because its geometry contains the same photographic imagery as the in-field video. This same process is at the root of this methodology and collection of three-dimensional geometry for the computer environment is part of that process.

Geometry of the site where in-field video recordings were obtained can be collected through various means. Common methods include laser scanners and survey equipment that directly measures points through laser emitted equipment, converting these points to three-dimensional data in the computer. Other common methods for generating computer geometry is through the use of photogrammetry. This can be performed using ground level photography or aerial imagery [20]. Publicly available databases can sometimes include LIDAR data of a site that can also be translated to three-dimensional computer geometry [21]. Even a drive through video can be analyzed and converted to three-dimensional computer geometry through the technique of videogrammetry [22,23]. Some objects that have known dimensions can be built to scale in the computer environment, such as buildings and signs, and commercially available assets already exist for a variety of vehicle make and models [24]. In the case of the research in this paper, a combination of the techniques listed above were used to generate three-dimensional geometry of the roadway sections that were video recorded.

In order to produce a complete scene, computer geometry of all the primary or relevant objects visible in the video must be built in the computer. These include both objects that might cause reflections (like buildings with lights) and those that receive them (surfaces like the roadway). *Figure 5* and *Figure 6* show the scene geometry utilized in this

FIGURE 5 - Computer model of environment where video was recorded

FIGURE 6 - Bird's eye view of computer environment

methodology, which includes data from scanning the scene, video tracking photogrammetry, aerial Lidar data, and pre-built assets.

In addition to geometry of objects, light sources such as the sun or sky dome and any man-made light sources may also need to be created, as these generate the color, light and reflection of objects in the computer environment. In the research presented here, the daytime adverse weather footage did not contain direct sunlight that cast shadows, as cloud cover diffused the light, but rather atmospheric sky dome environment that illuminated the scene through area lighting. As a result, the source non-adverse weather footage that was used in the production of the video realistic computer-generated scene was obtained during similar cloud coverage, just without rain or wet roadways. For this reason, the only light source that is going to illuminate the geometry of the scene and create reflections is the sunlight diffused through clouds and reflecting in the atmosphere. This light was model as computer-generated light source in the computer environment containing the physical geometry of the scene. The sky dome light, designed as an atmospheric light source, was created in Autodesk 3ds Max software and simulates light from a spherical dome or hemisphere above the scene environment to represent lighting coming from the sky. Because the in-field footage was taken on an overcast day, the shadows are much softer than those of a sunny day with no cloud cover. To replicate this effect, a High Dynamic Range Image (HDRI) was used with the sky dome light. This process involved obtaining a HDRI from the scene (which collected the effects of lighting in the environment) and mapping this image to the hemispherical sky dome. This step resulted in an image-mapped light source that provides "image-based lighting" for the environment [25] The HDRI was shot at the scene where the video was recorded and consisted of 216 photographs that were combined to create one 360-degree panoramic photograph of the scene with similar lighting and environmental conditions as the day the video was shot. To obtain a high dynamic range, multiple exposures were taken for each camera angle that captured slightly lighter and slightly darker photographs. These bracketed photographs were combined and the resulting HDRI is shown in *Figure 7*. Images taken by a professional grade camera in a raw format also provides high dynamic range images if multiple exposure images are not feasible.

The image based mapped sky dome resulted in lighting that created soft shadows similar to those observed in the

FIGURE 7 - HDRI image taken at the video location

in-field footage, and thus matching the lighting, colors, and contrast of the computer-generated scene to the in-field video.

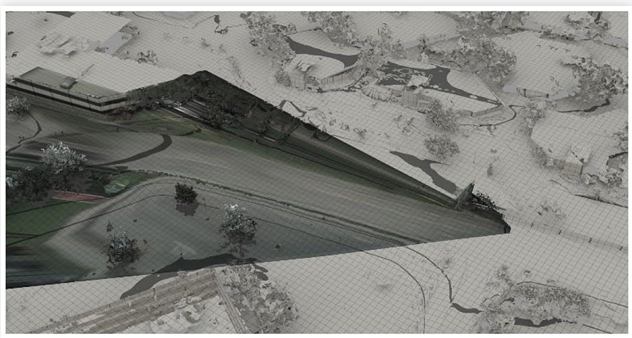
In addition to creating a computer-generated system for matching the lighting conditions during cloudy daytime weather, computer generated light sources that match nighttime conditions may also need to be created, depending on the purpose of the visualization and what effect, if any the lights have on visibility. The types of lights include streetlighting, security area lights, vehicles lights and lighting from nearby buildings or businesses that may affect the visibility in a scene. The lights that are relevant to the visibility from the driver's perspective may need to be computer generated since they illuminate objects in the scene and create the reflections that are relevant to adverse weather affect visibility. The production of these man-made light sources is discussed in the section "Nighttime Scenario" which specifically details the application of this methodology under nighttime rain conditions.

Tracking and Projection Mapping to Process the Video into a Three-Dimensional Environment

The three-dimensional computer geometry shown in *Figures 5 and 6* were utilized in the next step of video tracking and projection mapping. In this step, the daytime dry video footage was video tracked, and aligned to the computer geometry of the corresponding roadway location. Video tracking results in the creation of a computer camera that mirrors the movements of a camera through a computer environment as the actual camera moves through the real-world environment. Once tracked, the computer-generated camera is considered "aligned", since at each frame, the in-field video shows the same view of the real-world scene as the computer-generated camera has of the computer-generated scene. The video was tracked using accepted methodologies of video tracking [26,27]. To perform the tracking, the video was brought into AfterEffects™ and each frame exported as still images. Nuke™ was then used to import the individual frames and stabilize any bouncing, shaking and rotation of the camera. This sequence of frames was imported in PFTrack™, where objects identified in the video are assigned to corresponding objects in the computer scan data to scale and position the camera and correct for lens distortion. This step results in a computer-generated camera that matches the motion of the actual camera that recorded the original video. The video footage was then processed to apply textures from the video to the computer-generated geometry so that the geometry in the computer environment renders the same as in the video [28]. This step results in a photorealistic, simulated computer environment that looks the same as the original video footage. *Figures 8-11* demonstrate the process of projection mapping the original video onto the built computer geometry.

FIGURE 8 - Hi-resolution geometry of the environment where video was recorded

FIGURE 9 - Projection mapping of the video onto the computer model



As a comparison, *Figure 12* shows the original still image from the video and *Figure 13* is the corresponding computer simulated environment, rendered from the same vantage point.

Creating Modifiable Texture Parameters in the Projection Mapped Environment

The textures from each video frame can be assigned to the corresponding geometry in the computer environment to generate a photorealistic scene that matches the source video. In short, the color and value of each surface of the computer-generated element is derived from the pixel value of its corresponding object in the original video. However, the goal of this research was to include the adverse weather conditions, and their effect on driver visibility, within the photorealistic computer environment. To do this, the textures mapped to the computer geometry must be customizable. In other words, the material property (or texture) of the computer-generated geometry must be in a form that allows for editing of parameters such as diffuse and specular reflectance, index refraction and surface smoothness, since these parameters are what make the computer-generated scene appear to be interacting with rain.

In order to get the material property of the computer geometry to both be customizable and match the way these objects appear in the video, the program Houdini was used. This

FIGURE 10 - View of geometry from the roadway

FIGURE 11 - View of the results of projection mapping in the computer environment

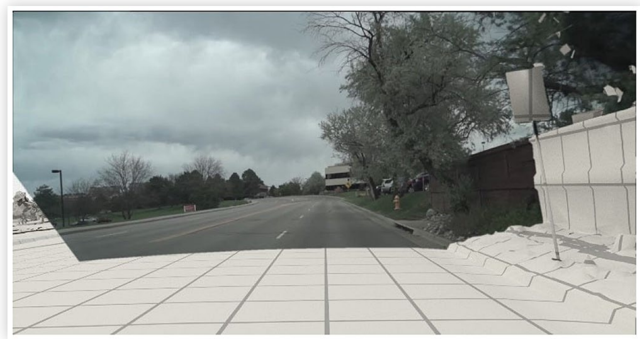


FIGURE 12 - Still image from the original in-field video

FIGURE 13 -Computer simulated environment with view along same roadway location

FIGURE 14 - Computer Environment Geometry

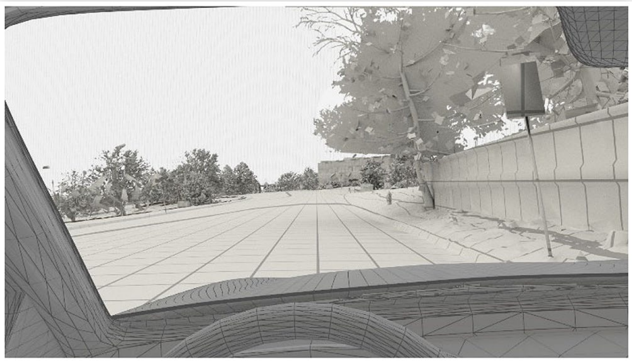


FIGURE 15 - Geometry with Houdini modifying the textures to be Customizable

program creates customizable and editable surfaces for the computer-generated geometry. These surfaces are pixel values that are based on the texture mapped surfaces from the video projection mapping. But because the projection mapped pixels are not editable, Houdini creates corresponding pixels that are editable with attributes that match the value, intensity color and position of the corresponding property observed in the video recording. This results in computer generated geometry that looks like the corresponding geometry in the video, but rather than an un-editable texture map, it can have attributes such as diffuse and specular reflectance and surface smoothness that can be adjusted to respond to light in the same manner that a wet surface does in the real world. *Figures 14* to *16* demonstrate the process of taking the projection mapped surfaces and using Houdini to duplicate the material look of the textures but in a form that is customizable for reflections and lighting.

Analyzing Adverse and Non-Adverse Weather in the Video Footage

Review of both the adverse and non-adverse weather conditions in the video revealed certain principles of the behavior of light during rainy weather that affects the driver's view.

FIGURE 16 - Houdini modified textures to appear wet

FIGURE 17 - Identification of viewable manifestations of the effect of rain on visibility

Primarily, the way the light interacts with the water droplets in the air, on the ground and on the windshield change the manner in which light enters the driver's view. Each interaction between light and the water distorts the light pattern received by the eye, making the objects appear different both when recorded in video, and recreated in a simulated environment [29]. Transmission loss through the water and veiling luminance can reduce luminance and change the contrast between objects and their background [30,31]. *Figure 17* is a still image from the video recording that included rain conditions. This figure includes notations summarizing some of the effects that rain has on visibility.

Observation of how rain affects the visibility of objects and light entering the driver's view can be generalized by comparing the adverse and non-adverse weather video footage. From this comparison, several observations were made: 1) As water collects on the surface of the roadway, it affects how rough or smooth the surface is. This in turn affects the road surfaces reflectivity. 2) Particles in the air, in the form of droplets, can affect the amount of light arriving back to the driver, in turn changing the objects perceive luminance and contrast. 3) Droplets on the windshield and movement of the wiper blades can create a surface that reflects and refracts light entering the windshield. All three of these properties and light effects have corresponding parameters in computer visualization. Tools for editing surface properties (smoothness and roughness), and light interactions on objects (refraction and contrast) provide the basic parameters that can be modified digitally to mirror the real-world behavior of light under rain conditions. The following section describes these parameters and adjustments to make a non-adverse video recording appear as if it is raining.

Computer Visualization Simulation for Mirroring Adverse Weather Effects

To get the computer environment to look like the live video requires adjusting the degree of reflectivity on the roadway and other surfaces. If there are particles in the air, this can also be added. Like a human eye, a computer-generated camera does not perceive an actual object, but rather the light reflecting off that object. Computer visualization tools allow control of the material properties, and the way light interacts with the geometry in a physically accurate way [32]. The principle behind this methodology lies in the ability for computer visualization tools to mirror physics in the real world, primarily that of how light behaves [33]. Computer visualization tools allow a user to rebuild the actual world in a computer environment and then visualize that environment in the same physics-based manner that the real world is viewed. Through control of properties like color, lighting, contrast, saturation and reflection of surface properties these physics-based algorithms reproduce a computer world such that it looks and responds in the computer the same as in the real world.

FIGURE 18 - Textures modified to have less rain than the original video

FIGURE 19 - Textures modified to have more rain than the original video

FIGURE 20 - Texture is modified (left) to match original video (right)

After creating a computer scene with geometry that has editable material and texture properties, adjustments were made to diffuse and specular reflectance, index refraction and surface smoothness of the geometry in the scene until the rendering of the material matched the corresponding live video of the weather adverse. This included adjusting the parameters of "Specular", "Roughness" and "Index of Refraction" (IOR) of objects upon which water would naturally accumulate. Primarily objects with horizontal surfaces such as the roadway and sidewalks. These parameters range from value of 0 to 1 with any increment in between, with the exception of IOR which has typical values falling between 1 and 2.5. The parameter of roughness, for instance, ranges from 0 to 1, with 1 being a rough diffuse surface and 0 being perfectly flat. For specular reflections, 0 to 1 corresponds to 0% to 100% of brightness for the reflection. The value of 1.33 was set for the IOR and corresponds to the index of refraction of water [34]. As an example, if a material was assigned a 0 for roughness, it would be perfectly flat, and if the specular reflection was set to 1, 100% of the light energy, scaled by the IOR, would be reflected off the surface, thus rendering the surface highly reflective. *Figures 18* to *20* show the adjustment of surface roughness and reflectance made to the computer environment materials such that the appearance of the surface in the computer environment matches the source video of rain recorded in the real world.

Comparison of Simulated Rain and In-Field Video of Rain

Two different comparisons were performed to evaluate how closely the computer simulated environment of rain matched the original in-field video captured under rain conditions. The first comparison is visual and shows results in *Figures 21* and *Figure 22*.

The two frames look substantially similar with regards to the effect rain has on the surface properties and lighting. The baseline non-adverse weather footage that was used in the creation of the simulated environment was obtained at a different time than the comparison rain footage. Because of this, temporary elements, such as signs on the roadside, or

FIGURE 21 - Resulting rendering from the simulated environment

FIGURE 22 - Source video image during rain conditions

other vehicles in the parking areas may be different. Additionally, the sky cloud patterns may differ, but these differences would not impact the overall visibility of the roadway and driving environment. Some of these differences, if they are relevant or significant to the end use of the simulated environment, can be updated such as adding vehicles, through the same computer modeling techniques described in this paper.

A quantitative comparison was also made, measuring luminance digitally, to determine the similarity between the image from the simulated environment to the image from the in-field video recording. *Figures 23* and *24* show the process of this comparison, including pixel sampling and measurements of luminance in the image. *Table 2* shows the relative difference between the images as a percentage. As demonstrated in the matrix, any difference between the simulated environment and the in-field video is minimal, approximately 1%-2%.

Nighttime Scenario

Visibility of objects available to a driver at night can be affected by the presence of man-made light sources. Headlamps of the vehicle are a primary light source, and for rural roads, and stretches of highway with no streetlights, headlamps may provide the only light source for seeing the roadway and

FIGURE 23 - Simulated environment image and measurements

FIGURE 24 - Source video image and measurements

TABLE 2 - Quantitative comparison of luminance in the images

Source	A (% White)	B (% White)	C (% White)	D (% White)
Source Video	29%	57%	65%	51%
Stimulated Environment	27%	58%	67%	50%
Difference	2%	1%	2%	1%

objects in and along the path of travel. While moonlight may potentially change the way the background and sky appear, it is not useful in augmenting the driver's visibility when the vehicle headlamps are operating [35]. Streetlights can affect the appearance of the roadway and the visibility of objects in and along the path of travel, and under certain circumstances, businesses with lights, and self-illuminated commercial signage may affect a driver's view.

Street Lighting from Known Lamp Types

Streetlamps come in several types including Metal Halide (MH), High-Pressure Sodium (HPS), Low-Pressure Sodium (LPS) and Light Emitting Diode (LED). Metal Halide,

FIGURE 25 - Reflections from metal halide and high-pressure sodium lamps

High-Pressure Sodium and Low-Pressure Sodium bulbs are all High Intensity Discharge (HID) bulbs. HID bulbs produce light by passing an electrical current between electrodes inside a glass tube filled with gas. A Metal-Halide light is filled with a mixture of mercury and metal halide gas while the HPS and LPS lights use vaporized sodium metal to produce light. The primary difference between them is the color that they produce. Metal Halide light produces a bright white light and the sodium lights produce an amber orange or yellow colored light. A Light Emitting Diode (LED) streetlight produces light by using an electrical current that flows through a semiconductor diode. LED lights can range in color but are typically white when used in streetlamps. On wet roads, these lights produce long reflections that streak vertically relative to the viewer. Changes in the temperature of the bulb, due to the gas or electrical current used in production of the light can change the color of the reflection too. *Figure 25* is a photograph showing the characteristics and color patterns of different streetlamps.

The research into nighttime visibility presented here included roadways where streetlights and other man-made light sources had an effect on the appearance of the roadway under non-adverse and adverse weather conditions. These man-made light sources were documented and replicated in the computer environment, since the light sources and reflections and illumination that they created needed to be included in the simulation. To model lighting in the computer environment, photometric lights can be used. Photometric lights use an ".ies" (an acronym for Illuminating Engineering Society) file format which contains the specifications of the light including the shape and falloff of the light, and the light distribution pattern. The IES file format has been widely utilized in architectural, engineering, and design communities [36, 37]. To incorporate the effects of street lighting where the streetlight specifications are known, the following steps were performed:

1. Create a light in the computer environment
2. Import the desired IES file format and assign to lights
3. Adjust the color temperature according to the manufacturer specifications

FIGURE 26 - Aerial image of intersection and streetlamp

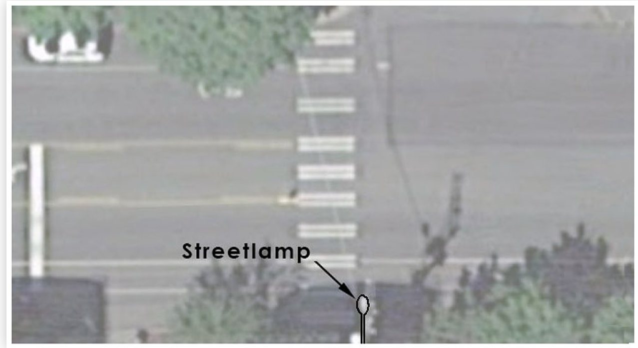
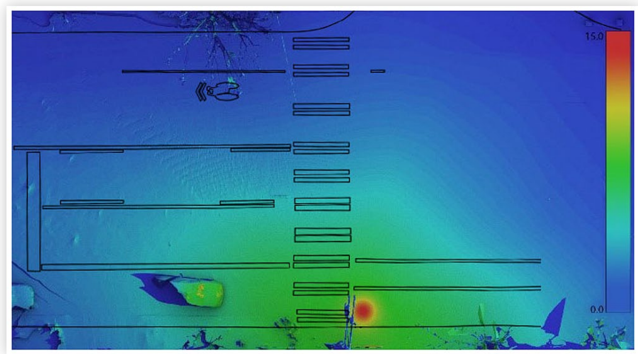


FIGURE 27 - IES photometric light distribution pattern



4. Adjust light type, orientation, intensity and exposure to match video footage

A photometric web file in an IES file format that matches the light source observed in the real world was assigned to the computer light source. A photometric web is a 3D representation of the light intensity distribution of a light source. It contains data defining the vertical and horizontal luminous intensity of a computer-generated light source and is derived from the IES file. The IES file distributes the light energy in the computer software in the same pattern and spread as the lamp in the real world. After this is done settings can be adjusted so that the color temperature and light intensity matches the real-world light.

As an example, the lighting conditions created by a streetlamp at one of the intersections where video was taken under adverse and non-adverse weather is analyzed to illustrate how IES files can be utilized in simulating light sources. *Figure 26* shows an aerial image denoting the position and orientation of the streetlamp at a crosswalk. *Figure 27* shows this same perspective of the crosswalk in a three-dimensional environment and the photometric light distribution of the IES file color coded for intensity. In this case, blue represents little to no light energy, and red represents the area of the roadway receiving the most light energy. *Figure 28* is a computer rendering of the IES file that shows the light intensity and distribution from a top view.

FIGURE 28 - Computer rendering of the IES photometric light file

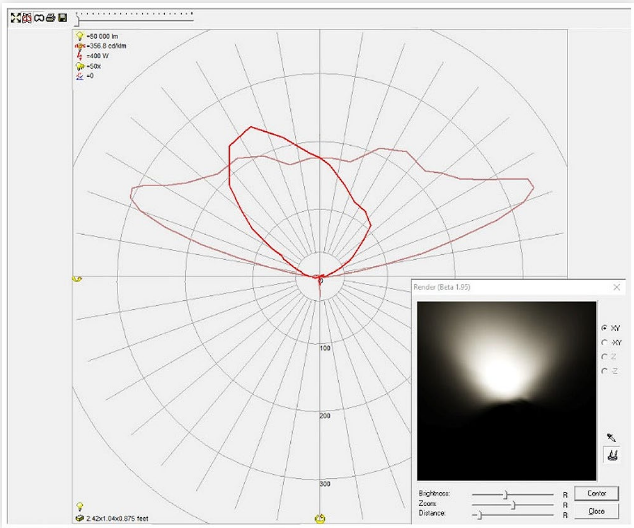


FIGURE 29 - Lux measurement locations taken in the crosswalk

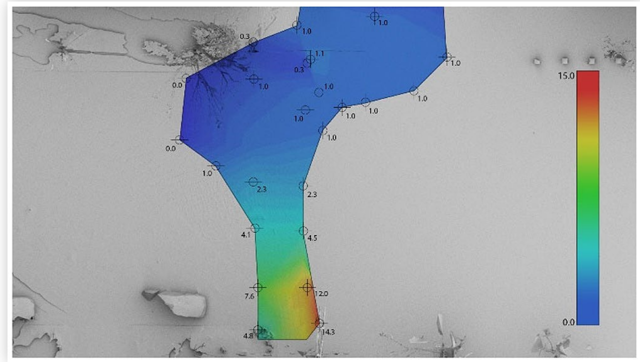


FIGURE 30 - Comparison of the photometric IES light and lux measurements

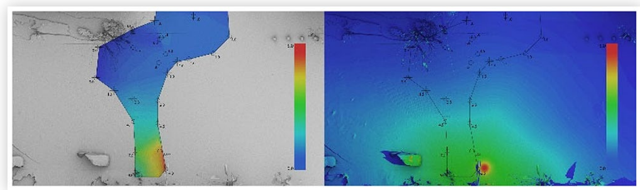


FIGURE 31 - Secondary lighting and reflective sources

Street Lighting from Unknown Lamp Types and Other Light Sources

If the lamp assembly is unknown or it is not possible to get an IES file, the roadway can be mapped with a lux meter to determine the light distribution pattern of the light, collected in a similar manner as the "web" patterns in the digital files. To demonstrate this process, lights were made of the same crosswalk intersection without using IES files, but rather relying on light values obtained at the scene. Lux measurements were taken at ground level in the crosswalk every 10 feet starting directly under the light and continued across the street at the two outside edges of the crosswalk. Measurements were recorded until the meter was unable to read a difference between the streetlight and the ambient light. *Figure 29* is a top view of the crosswalk showing the light readings documented at each point in the crosswalk and *Figure 30* is a top view of the crosswalk with the lux values overlaid on top of the light pattern produced by the IES photometric light. A third alternative includes photographing the area where light is distributed using calibrating photographic techniques and referring to the light patterns exhibited in these photographs as basis for modeling the lamp.

In this research it was determined that all methods, either by assigning IES files to the streetlights in the computer environment, mapping the light distribution from hand measurements in the field, or referencing calibrated nighttime photographs work equally well at producing the effect of the lights they replicated, provided that adequate information is obtained about the lamps, or the pattern of light as it appears in the scene.

Other light sources considered in this research include secondary lighting such as vehicle taillights and headlamps, traffic signal lights, self-illuminated signage, and other ambient light sources. Reflective signs were also considered since they are illuminated by headlamps or other direct light sources, and the reflection can be seen on the roadway surface. *Figure 31* is an example of secondary lighting and reflective signage on the roadway.

To replicate these light sources, or the effect of these lights in the scene, a method referred to as texture-based emission was utilized and involved the following process. First, the pixels from the brightest areas of the image are isolated from the original footage. This was done using Nuke™ by means of a luminance key which allows pixels below a specified luminance threshold to be selected and given a black color leaving only the very brightest regions of the image unaffected. After an image that contains only the high contrast, highly reflective and brightest portions of the scene's light sources is created, this image is re-projected as a texture map back to the scene from the same perspective as the original image. Areas of the image below the luminance threshold, such as the roadway, sky and trees are turned black in color. When a pixel is used to emit light, a black pixel emits no light, and the remaining colored pixels in the image will emit light with their respective colors. This results in bright pixel value textures that are in the correct position in the three-dimensional scene. After the location of these light sources is determined, these pixels can be used as light sources to affect the lighting in the scene.

Sample #1 of Nighttime Simulated Rain

Video footage was captured on two separate nights of an intersection under adverse rain conditions and clear, non-adverse conditions. The streetlights at each corner of this intersection were High-Pressure Sodium luminaires. *Figures 32 and 33* depict still images of the original non-adverse and adverse weather video footage.

Methodologies described in this paper were used to create the computer-generated scene environment. Laser scanners were used to map the intersection and the roadway leading up to it to produce a three-dimensional point cloud. This point cloud was imported into 3DS Max and scene geometry was created from it to accurately portray the scale of the real-life environment. The geometry includes relevant objects like the roadway, the streetlights, street signs and traffic signal lights so that the lighting and reflections can be accurately located.

FIGURE 32 - Still image from video recording of non-adverse conditions

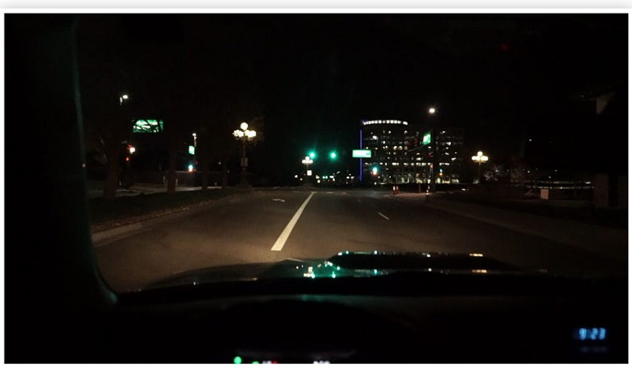


FIGURE 33 - Still image from video recording of adverse conditions

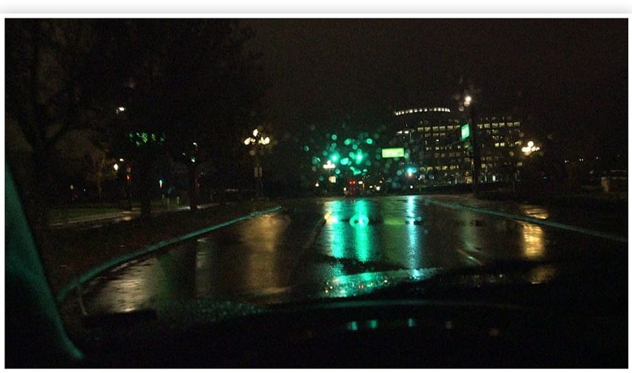


Figure 34 and *Figure 35* show the scene geometry utilized in this methodology, which includes data from scanning the scene, and pre-built assets.

After building the three-dimensional environment shown in *Figures 34* and 35, this model was utilized in the tracking and projection mapping processes. The nighttime dry footage was video tracked and aligned to the computer environment of the intersection. A computer-generated camera was created that follows the movements of the actual camera, and the pixel properties and values from the video were assigned to the corresponding geometry in the computer environment. *Figures 36* to 39 demonstrate the process of projection mapping

FIGURE 34 - Computer model of environment where video was recorded

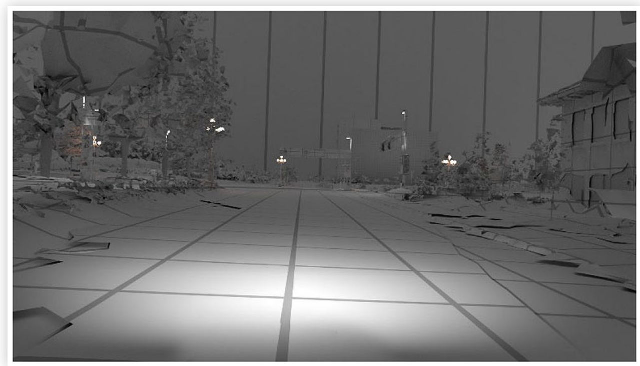


FIGURE 35 - Computer model of environment where video was recorded

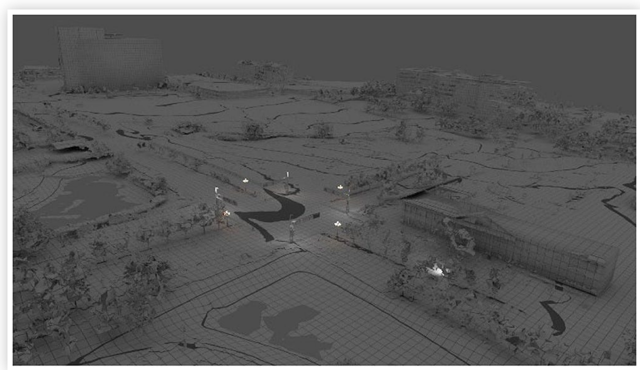


FIGURE 36 - Hi-resolution computer model of environment

FIGURE 37 - Projection mapping of the nighttime video on to the computer model

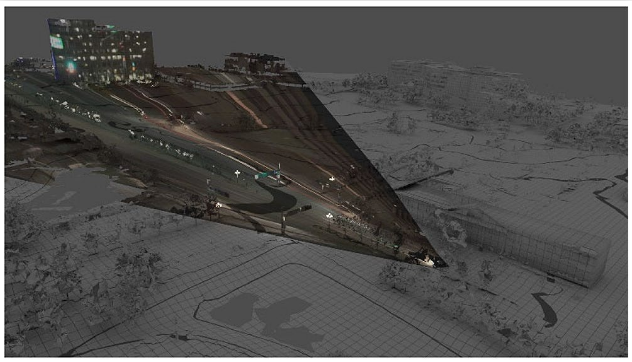


FIGURE 38 - Driver's view of the computer model

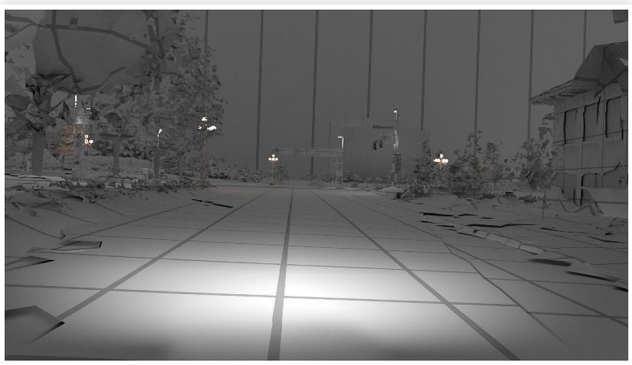
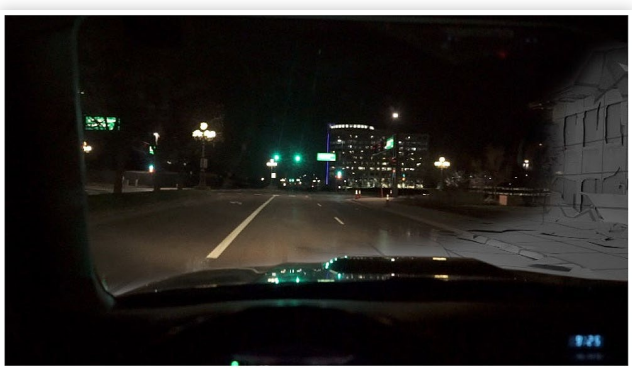


FIGURE 39 - Video realistic texturing of the computer environment



the original video footage onto the computer-generated geometry. In addition to building geometry of objects, the geometry of light sources such as traffic signal lights, streetlights, and self-illuminated signs were also built in the computer model to simulate the light, color and reflections of the light sources.

For streetlamps, IES files with the correct streetlamp type were imported and assigned to the light sources. These lights had parameters that were adjusted until the results on the roadway matched the color temperature, orientation, characteristics and intensity as observed in the video

FIGURE 40 - Resulting rendering from the simulated environment

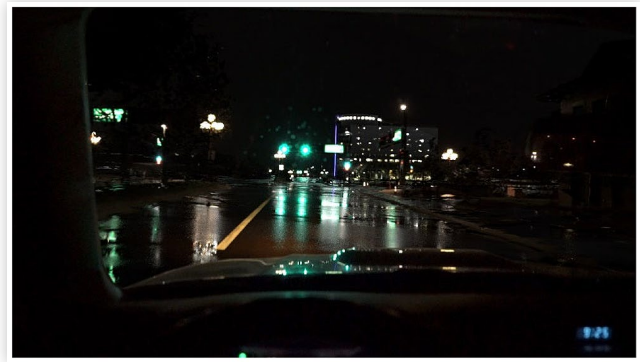
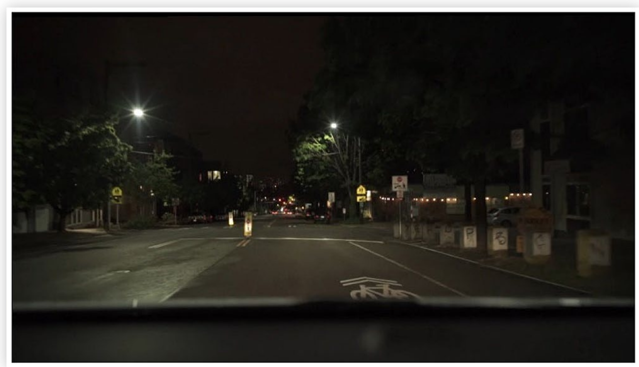


FIGURE 41 - Still frame of the drive through video footage in dry conditions



footage. After the lights are created and properly adjusted, the effect of the lights on the roadway, namely reflections on the road, were created by adjusting the specularity and roughness of the shader of the roadway surface geometry to match that of a wet road surface. *Figure 40* depicts the results of creating a computer simulated rain environment, and the effect of reflections from streetlamps on the road surface.

Case Study of Rendering Rain When Site was Visited During Dry Weather

An analysis was performed using the methodology described in this research, to modify video footage taken at an intersection in dry conditions such that it appears as if it was taken during rainy conditions. This intersection included 400w Halogen streetlamps, retroreflective signage, and lighting from nearby buildings. *Figure 41* depicts a still image from the video showing the intersection under non-adverse weather conditions.

FIGURE 42 - Computer environment and texture mapped scene

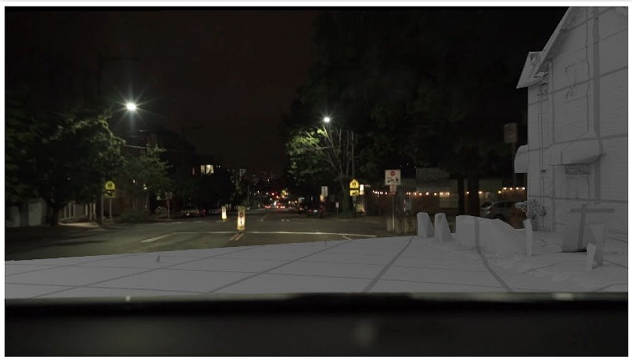
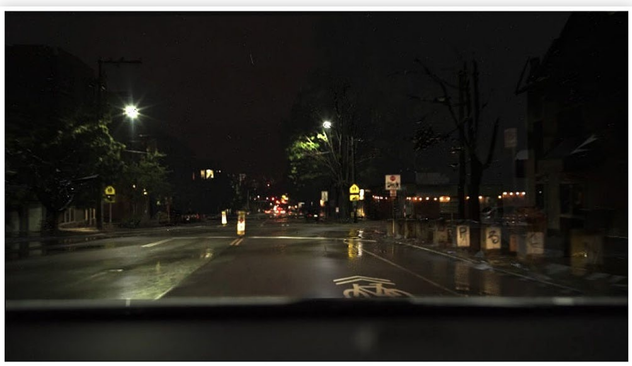


FIGURE 43 - Resulting rendering from the simulated environment



The scene was scanned and converted to a three-dimensional model, then video tracked to generate a camera, and the textures mapped to the computer geometry to create the baseline simulation environment that did not have rain. *Figure 42* shows the simulated environment with non-adverse weather.

To generate the lights in the environment photometric lights using an IES streetlight were added to the scene in their respective locations. Photometric light clusters were added to approximate the lighting from the vehicles' headlamps [38]. The remaining lighting from the buildings and distant objects were included by first isolating the pixels from the original footage then assigning them to the emission channel of the shader as discussed previously. To generate the roadway texture to represent rain, the parameters were adjusted to yield a moderately wet surface with pooling in areas containing irregular depressions as documented in the scan data. The index of refraction was set to 1.33, which corresponds to water [39]. The roughness and specularity were adjusted to have a rougher surface with less intense reflections in areas with less water and a smoother surface with more intense reflections in areas where the water has pooled. These parameters were adjusted to represent the effect of rain based on the body of rain footage captured during the course of this research. The resulting rendering, showing moderate rain at the intersection is shown in *Figure 43*.

Discussion

During the 10-year span between 2010 and 2020, the authors collected live video footage at sites around the United States that showed the effect of rain, snow and fog. When driving in an area where one of these adverse weather conditions was occurring, video footage was obtained and catalogued. Then, when back in the same stretch of roadway at another date, and the weather was clear and non-adverse, video recordings were again taken and catalogued. While Table 1 shows 11 sets of sites where video was recorded of adverse and non-adverse weather, this is only a portion of the total sites visited, and total video footage recorded. Some sites had rain and snow mix, some sites had fog, some sites were substantially similar to the daytime or nighttime rain conditions already recorded. Nonetheless, all the weather sites were informative in understanding how rain affects driver visibility, even if not specifically included in this paper. Software presented in this research, while widely utilized and featured in other peer reviewed research and testing [40, 41, 42], is expensive and robust, and requires solid knowledge of the software by the user to perform the techniques described in the paper. The equipment for scanning the scene, cameras for video recording drive through, and the need to model geometry in the computer, likewise can be expensive and time consuming. Hence, while the techniques and methods presented here are shown to be accurate, they can be expensive, time consuming, and require in-depth knowledge of techniques and software applications.

Conclusion

The methodology in this paper utilizes video projection mapping techniques to generate a video based simulated environment. Since the lighting, textures, and material properties of the computer environment can be controlled and modified, the simulated environment can be adjusted to visually represent rain conditions. can be accurately represented. This method results in video realistic visibility of objects where reflections, refraction, and luminous properties of the materials can be adjusted to make the environment appear under heavy, moderate or light rain conditions. When measuring the accuracy of the simulated rain environment to the source video footage, the contrast and lighting values in the simulated visualization are approximately within 1% to 2% of the comparison in-field video. This paper contains only still images, since it is in a printed form, though at the time of publication, real time playback file of both the source in-field videos and final simulated visualizations can be requested through Kineticorp.

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Contact Information

William Neale, M. Arch.,
Kineticorp, LLC,
(303) 733-1888,
wneale@kineticorp.com, www.kineticorp.com

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