Road Subsystem Workbook

Domain Workbook for the Road Subsystem

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Chapter 1

Introduction

Define: **road**. We're all experts in autonomous driving. Surely we all know what a road is, right?

Or maybe, just maybe, we all use wildly or, worse yet, subtly different definitions depending on what sort of problem we are focused on at the moment.

Forgetting about your particular algorithm or area of focus, there surely must be some set of fundamental real-world concepts... things in the driving environment in addition to road, like lane, lane division, median and so forth that we can all agree on. In fact, the names aren't so important, but the concepts are. The three sides of a triangle can be equally well described with $a^2 = b^2 + c^2$ and $b^2 = d^2 + q^2$. It's good to agree on names, but much more important to agree on the underlying elements. Our models propose both names and semantics (and any resultant rules and constraints among them). We are primarily concerned with the semantics, but we need the names to have a conversation.

Why is it so important for safety, testing and design purposes to pin down the meaning of a supposedly self evident term like a *road*? We could just as easily ask why it is so important for aerospace engineers to have a definition for an ellipse. Now, we're no rocket scientists, but there are certain behaviors available to an Ego Vehicle on a *road* that would be quite dangerous were it in, say a parking garage. Less extreme distinctions are also important. When a freeway splits off to an exit, are you looking at one road or two? Does it matter? What are the logical consequences of one definition vs. another? How many roads are you looking at when you observe a roundabout intersection with three entrances?

The Road Subsystem and its class model attempt to nail down a detailed, useful and algorithm/technology independent definition grounded in math and logic. This subsystem consists of a single class diagram and descriptions of each diagram element such as class, attribute, relationship and so forth. Every element on the diagram is described (or at least should be!).

This class model describes the fundamental structure of the roadway: lanes, lane divisions, road segments, road edges, traffic flow, etc. Having defined roads and their structure, we obtain the lego-like semantic building blocks we will need to define more complex aspects such as intersections, lane turns, crosswalks and onward. These will be detailed in other connecting subsystems.

Chapter 2

Class model

A complete Executable UML model consists of three interlocking facets. These are:

1. A class model which formalizes data/logic/constraints
2. A set of state models (synchronization)
3. A set of activities (computation)

In this chapter we focus on the class model facet. This facet defines the abstractions, data, logic, rules, policies and constraints that characterize a given subsystem.

The model consists of a diagram and a set of descriptions that document each element found on the diagram. A thumbnail of the diagram is included in this document for completeness, but we recommend getting your hands (or screen) on the full size version which should be easily located in the same repository.

Class descriptions appear first and are organized alphabetically for fast reference, like a dictionary. To make sense of these descriptions you probably want to start with a central class and then walk through the diagram looking up classes as you encounter them rather than reading from A to Z.

Each non-referential attribute (those without an R number) is described along with its class.

The next section describes all relationships in ascending numerical order. For each relationship there is a description of its meaning, multiplicity and how it is formalized in terms of referential attributes. Any additional constraints on the relationship are also included.

Class diagram

The Road Subsystem is focused on defining just what a “road” really is. What are the fundamental components necessary to precisely describe the Roads we observe in the real world? This model then sets the stage for exploring more complex aspects such as intersections, lane turns, crosswalks and so forth which we do in the adjacent subsystems.

The figure below shows the class diagram for the Road subsystem of the Vehicle Guidance domain. The graphic uses a subset of UML class diagram notation.

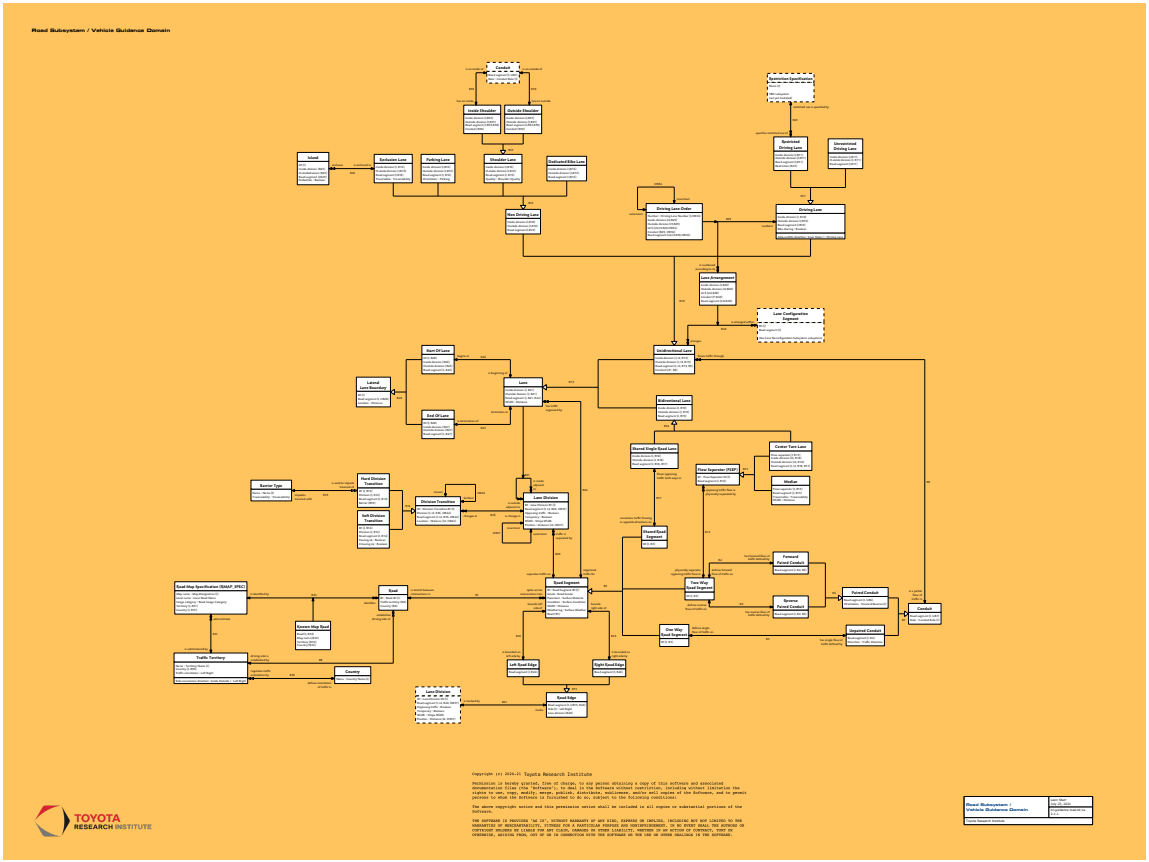


Figure 2.1: Road Subsystem Class Diagram

Classes

Barrier Type

There are numerous possible styles of barrier from water filled barricades to short cement curbs to cable fences and so on. We can't inventory them all, but we can classify them in terms of traversability. You can't drive through a cement wall, but you can hop over a short curb or plow through a row of bushes if necessary in an emergency.

Identifiers

1. Name

Attributes

Name

A descriptive name such as "water filled barricade" or "cement curb"

Type: Barrier Type Name based on the system Name type

Traversability

Is it possible (not necessarily legal) but physically possible to traverse this Barrier Type? This information is helpful in an emergency. When you as a human drive along, say in the innermost lane and bicycle sudden appears in front of you, you may consider the possibility of swerving into the grass. But you would not necessarily swerve into a cement column. For humans at least, in an emergency, the physical traversability of a barrier can be extremely relevant.

Modelers note: I made a similar distinction on a motorcycle fishtailing between a cement median and a soft shoulder at 70mph on Highway 17 in Santa Cruz, California. I am alive and writing this today because, at the last moment of control, I veered to the (relatively) soft 'traversability' of the outside shoulder. –LS

Type: `[ hoppable | intrusion damage | hard ]`

Note: This value set is just an initial guess as to what classifications would be useful.

Bidirectional Lane

If traffic can flow in both forward and reverse directions in the same Lane, it is bidirectional.

There are two known situations where this is permitted to happen.

The most common case is the country road or narrow alleyway where there are no lane markings and the entire width of the Road is open to traffic in either direction. Vehicles just pull over and squeeze past each other to get by.

The other possibility is a central turn Lane where vehicles approach from either direction for a short distance to make a turn across the roadway.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Center Turn Lane

This type of Lane is designed to facilitate turns off of a city street across oncoming traffic with as little disruption to the main flow as possible. These will always be turns toward the inside of the Road Segment. That's left with right handed traffic and right with left handed traffic. In the USA these are often called "center left turn lanes".

When turning off of a street, vehicles can queue into the Center Turn Lane, wait for oncoming traffic to pass and then complete the turn. This may be a full left turn or, if not specifically prohibited, a u-turn.

Figure 2.2: Center Turn Lane

Center Turn Lanes are commonly used to enter a city street. For this usage, a vehicle enters the street, crosses the opposing traffic Conduit first, waits for a gap and then enters the Forward Paired Conduit.

Center Turn Lanes are often marked with turn arrows to indicate where a turn outlet (such as a parking lot entrance) is available. But do not confuse these with dedicated turn lanes. A dedicated turn lane belongs to a specific Conduit. Since traffic can flow in both directions in a Center Turn Lane, there is no Conduit. The turn arrows in a Center Turn Lane are purely advisory. Traffic is always allowed to flow both ways in a Center Turn Lane.

Identifiers

1. Inside division + Outside division + Road segment
2. Flow separator + Road segment

I1 is unique for any kind of Lane

I2 indicates that Flow Separators are numbered uniquely within each Road Segment

Attributes

(No non-referential attributes)

Conduit

Merriam-Webster's online dictionary defines a "conduit" as:

1: *a natural or artificial channel through which something (such as a fluid) is conveyed*

For our purposes, we consider the flow of traffic. A Conduit represents a regulated flow of traffic in a single direction.

The established term "carriageway" is somewhat synonymous, but only in cases where a Conduit is bounded by physical barriers. On a Road Segment with a single painted line separating opposing traffic, there is no established term to refer to a set of Lanes flowing traffic in the same direction.

So a Conduit is, in fact, a superset of what "carriageway" appears to define.

Identifiers

1. Road segment + Role

Since no more than one type of Conduit may be present in a Road Segment, we can use the Road Segment.ID in conjunction with the Conduit.Role to distinguish one Conduit from another

Attributes

Role

Given some Road Segment, a given Conduit must be forward, reverse or unpaired (in the case of a One Way Road Segment). We get conclusion simply by taking the union of the subclass names.

Thus we can talk about `RS1-F` (the forward Conduit in Road Segment `RS1`, for example.

Type: `[ F | R | U ]` forward, reverse or unpaired

Country

This is a political state or nation (Merriam-Webster) that, for our purposes, establishes or adopts its own set of traffic policies. Common examples are USA, Japan, China, UK, France, etc.

It is tempting to assign attributes here such as Traffic Orientation to describe whether or not traffic flow is right handed as well as other Country specific properties. For some Countries, like Japan, this would work. But there are Countries that establish distinct Traffic Regions where the rules vary. So, for our purposes, Country is simply a way of helping define Traffic Regions.

Identifiers

1. Name

Attributes

Name

The officially recognized name

Type: Country Name

Comment: We may discover policies that apply Country-wide, independent of Traffic Region and add appropriate attributes here later.

Dedicated Bike Lane

There are many places where bicycles can travel. Not all of them are of interest to drivers of a vehicle. For example, a bike path that is entirely separate from the roadway, winding alongside it somewhere in the trees is not necessarily of interest.

On the other hand, a lane that flows inside of a Conduit certainly is. Here a Dedicated Bike Lane is considered to be a pathway dedicated to bicycle traffic incorporated into a Conduit. Depending on the location and markings associated with such a Lane, it may or may not be possible or permissible to cross into or over the Lane. These properties are established by the Lane Division type on the inside and outside edges of the Dedicated Bike Lane.

Figure 2.3: Dedicated Bike Lane

Vehicular traffic is forbidden from traveling, by definition, in a Dedicated Bike Lane. Those lanes which are marked inside of Driving Lanes where all or a portion of the Driving Lane is effectively shared with cycling traffic is abstracted as property of a Driving Lane rather than as a distinct type of Lane.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Division Transition

As you drive along, Lane Divisions not only come and go as Lanes merge and split, but they may also change shape and policy. A division that allows passing, for example, may change policy to forbid passing.

The physical form of a Lane Division may also change. What was once a painted stripe that can be driven across may transform into a concrete barrier.

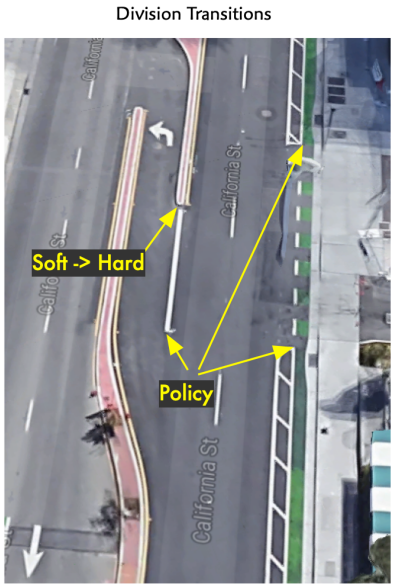


Figure 2.4: Division Transition

The point at which a Lane Division changes changes to or from a physically non-traversable barrier or changes policy or both makes a Division Transition. Between any two consecutive Division Transitions on a given Lane Division, we assume that the policies and traverse-ability does not change.

Identifiers

1. ID + Division + Road segment

Attributes

ID

An identifying value

Type: Based on Nominal

Location

The distance ahead of the Ego Vehicle in the Lane Division where the transition occurs. The Division Transition currently active (adjacent and extending away from the Ego Vehicle) is considered at 0 units of distance away, so transitions don't go negative as we pass them. We'll ignore/drop any Division Transition once its next further transition on the same Lane Division reaches 0 distance.

Type: Distance

Driving Lane

This is a Lane where vehicles are permitted to travel forward indefinitely responding to the usual traffic rules and constraints.

This in contrast to types of Lanes where vehicle traffic is impossible, not allowed or discouraged such as Shoulder, Dedicated Bike, and Exclusion Lanes.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

Bike sharing

Whether or not bicycle traffic is explicitly permitted to share the Driving Lane. By explicit, we mean that there are some markings or signs to designate that a particular Driving Lane must share the road.

Type: Boolean

Driving Lane Order

In California and many other places, it is customary to number Driving Lanes from a Conduit's innermost Lane Division outward. So the innermost lane is 1 incrementing out to the Driving Lane along the outer Shoulder (if one exists). The numbering may change if Driving Lanes are reconfigured down the Road. Thus, a merge in the innermost Driving Lane will result in the elimination of that Driving Lane and decrementing the number of each Driving Lane to the outside.

Identifiers

1. Number + LCS + Road segment
2. Inside division + LCS + Road segment
3. Outside division + LCS + Road segment

I1: California lane numbers are unique within each Lane Configuration Segment (LCS). Each time the Lanes are reconfigured (merge, split, etc occurs) the numbering must be re-evaluated. The number of any given Driving Lane can change from LCS to LCS within the same Conduit.

I2, I3: Rather than using the California lane number, you can just use the ID of either the inner or outer Lane Division. You still have to combine it with the LCS and the **Road segment** since a given Lane Division can participate in more than one Lane as it spans Lane Configurations (merging, diverging, etc) and re-pairing to form other lanes.

Attributes

Number

In California, Driving Lanes are numbered sequentially, beginning with 1, from the innermost to outermost within a Conduit. Since there is no internationally accepted numbering method, this one is proposed.

Type: Driving Lane Number based on the Ordinal type (1, 2, . . .)

End of Lane

The location up ahead where a Lane terminates.

For example, the Ego Vehicle might be approaching a merge where its Active Driving Lane ends. Or maybe it ends in an upcoming Intersection Interface.

Identifiers

1. ID + Road segment

Lateral Lane boundaries are numbered uniquely within a Road Segment.

Attributes

(No non-referential attributes)

Exclusion Lane

At certain points in a Conduit, space may open up to form an area where travel is not permitted or is physically blocked. This space is classified as a Lane since it takes on a similar geometry, it is defined by Lane Divisions and is part of a single Conduit. Since an Exclusion Lane is part of a Conduit it should not be confused with a Median which separates Conduits.

Here is an Exclusion Lane between two Driving Lanes:

Exclusion Lane containing a hard Island

Here is an example where a raised platform excludes traffic inside a Conduit:

Identifiers

1. Inside division + Outside division + Road segment

Attributes

Traversable

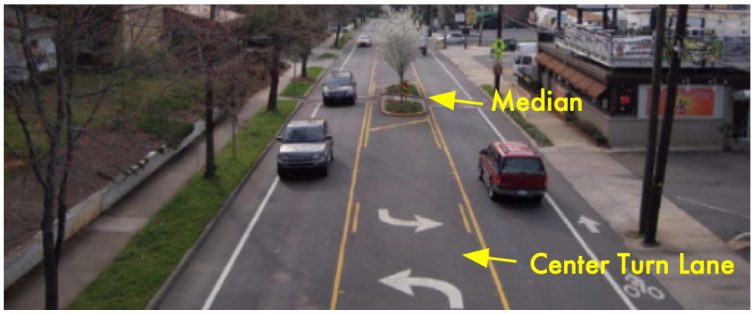
Similar to Median, this describes whether or not it is physically possible to cross into an Exclusion Lane.

Type: Traversability
[hard | soft | open]+

Flow Separator

The space (if any) provided between opposing Paired Conduits in a Two Way Road Segment can be designed for one of two purposes. The space is either blocked off with a physical obstruction or painted markings in which case it is a Median or the space is occupied by a Center Turn Lane.

A Flow Separator occupies the space between two opposing Paired Conduits. Here is an example with two types of Flow Separator on the same Road Segment:



Identifiers

1. Inside division + Outside division + Road segment

Attributes

ID

A unique number is assigned to each observed instance.

Type: Flow Separator ID based on the Nominal type

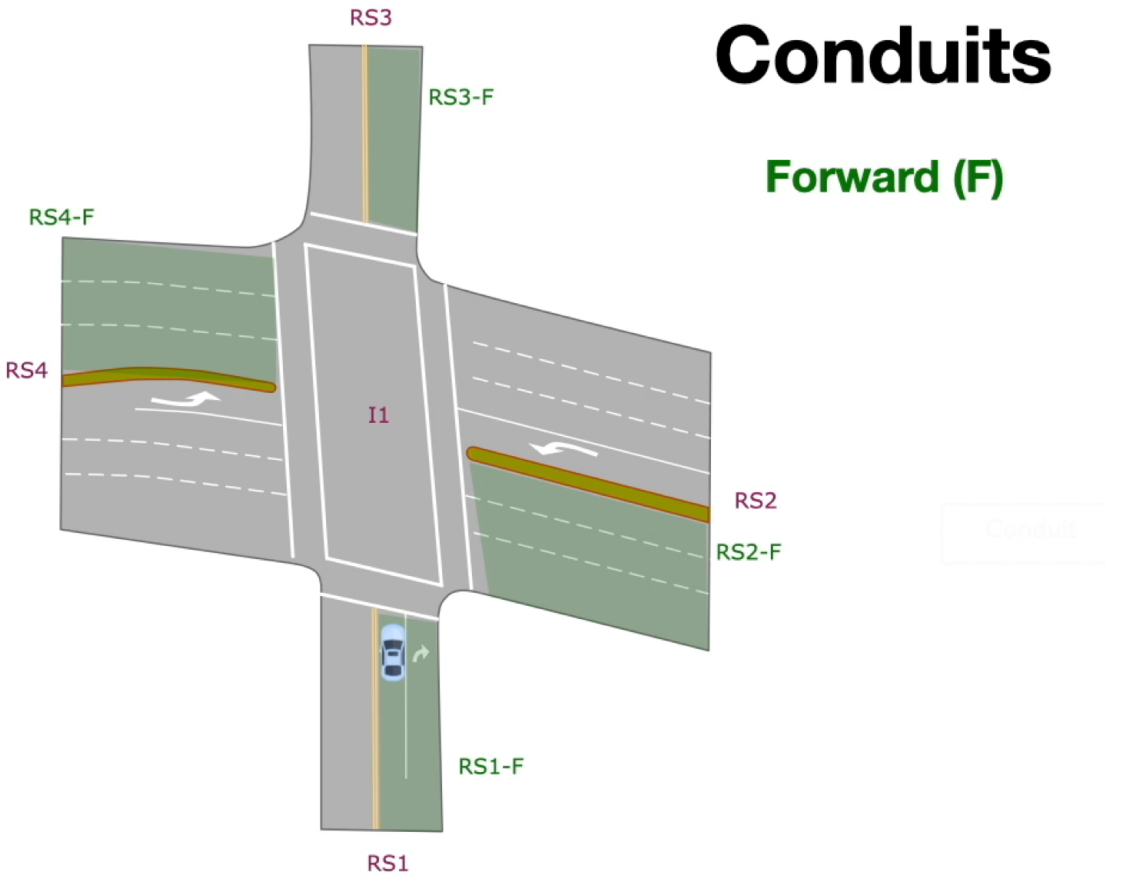
Forward Paired Conduit

In a Two Way Road Segment, this is either the Conduit where the Ego Vehicle is currently located, or some Conduit in a different Road Segment where the Ego Vehicle could enter, moving in the legally allowed direction of traffic.

If the Ego Vehicle is actually in this Conduit, the Ego Vehicle should be pointed in the direction of legal traffic flow. In rare and, hopefully temporary cases it might not! Perhaps there is ice on the road and the Ego Vehicle has spun around and is presently pointing the wrong way. Or perhaps a navigational error resulted in a wrong way entrance. Even though the Ego Vehicle may be pointed backwards, its Conduit is still considered to be a Forward Paired Conduit. In other words, an Ego Vehicle cannot, by policy, ever be in a Reverse Paired Conduit.

If the Ego Vehicle is not in this Conduit, it must be one that is seen to lead in the forward direction relative to an Ego Vehicle's current Conduit direction.

Say, for example, that the Ego Vehicle's Forward Paired Conduit is pointed northward toward a four way Angular Intersection. The innermost Conduit running eastward is considered forward as is the outermost Conduit running westward. Also the northward innermost Conduit straight across from the Intersection is also forward. This example works in either a right side or left side driving Traffic Territory.



In the figure above, even if the Ego Vehicle were spun around in the wrong traffic direction for some reason, all of the green shaded Conduits would be considered ‘forward’.

Identifiers

1. Road segment

Attributes

(No non-referential attributes)

Hard Division Transition

The beginning of a new Barrier Type is marked by a Hard Division Transition. This could be a transition from no Barrier Type to any kind of barrier or it could be a significant change in Barrier Type, say from a curb height median to a brick wall.

Identifiers

1. ID + Division + Road segment

Attributes

(No non referential attributes)

Inside Shoulder

A Shoulder Lane on the inside of a Conduit.

Identifiers

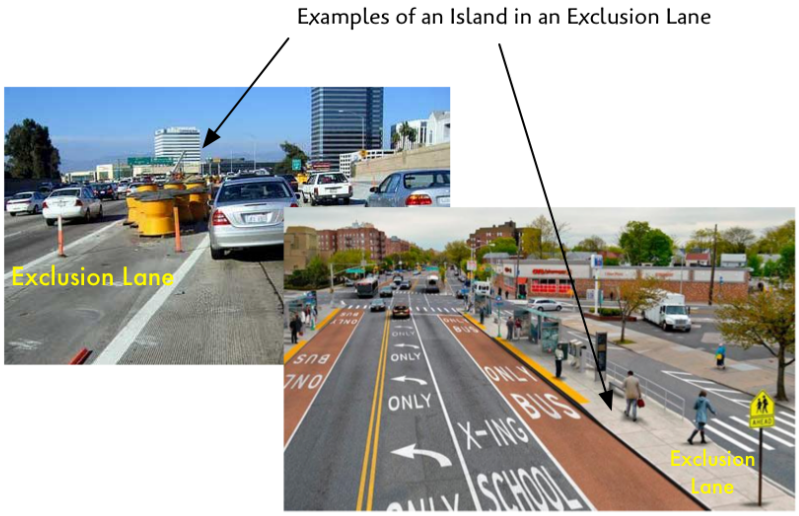
1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Island

An elevated region or physical obstacle, obstacle group or barrier within an Exclusion Lane constitutes an Island. Here are some common examples of Islands:



Identifiers

1. ID + Road segment

Attributes

ID

Islands are numbered as they are discovered.

Type: Island ID based on the Nominal type

Pedestrian

Whether or not there could be pedestrians gathered in the Island as would be the case with a bus stop or train platform. (There don't have to be any pedestrians there at the moment). For example, this would be false if the Island consisted of water tanks barriers and true if it were a train platform.

Type: Boolean

Known Map Road

When the Road is correlated with a Road Map Specification we know what map road we are on. Thus, we are on a Known Map Road.

Otherwise, the Ego Vehicle is on a Road, but the map name of the Road is unknown.

Identifiers

1. Road

There can't be more than one Road Map Specification associated with the same Road. We either know what Road we are driving on or we don't.

Attributes

(No non referential attributes)

Lane

A Lane is a path within a Conduit where a traffic policy applies. The policy may specify the direction of traffic, the type or purpose of traffic (bikes, taxis, cars) or possibly no allowed traffic at all. If traffic is allowed, it may flow in only one direction as determined by the surrounding Conduit.

Not all Lanes are drivable. Sometimes Lane Divisions will open up into a Y shape to accommodate a set of diagonal stripes or a barrier or a temporary median of some type. This region is considered to be a Lane because of its shape and boundaries.

Lanes

Inner division	Outer division	Road segment
LD3	LD2	RS1
LD2	LD1	RS1
LD1	LD5	RS1
LD5	LD7	RS1
LD7	LD8	RS1
LD8	LD6	RS1

Lane Divisions in a single Road Segment (RS1)

The space between two tightly adjacent stripes close enough together to be interpreted as a complete Lane Division will not be construed as a Lane. A double yellow line indicating the separation of traffic flow in the USA is one such example. Two closely adjacent, but distinct Lane Divisions will, however, define a Lane even when there may be inadequate width for a vehicle to travel within it.

Note that this imposes a requirement on underlying perception and symbology to properly classify Lane Divisions.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

Width

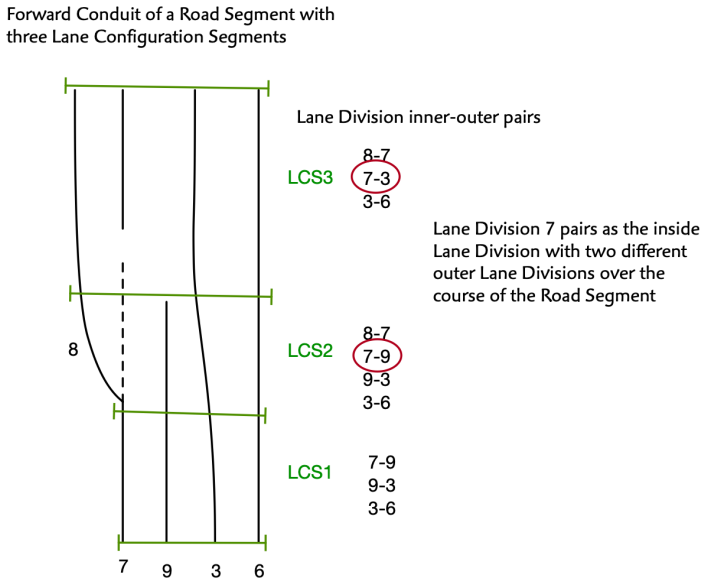
The average distance between the inside and outside Lane Divisions from the front of the Ego Vehicle up to some prescribed distance (which may vary with Ego Vehicle speed) ahead of the Ego Vehicle.

Comment: Presumably we'll have appropriate attributes/formulas for computing this distance incorporated into this model. But they have not been modeled yet

Type: Distance

Lane Arrangement

A Lane Configuration Segment marks off a set of adjacent Driving Lanes in the same Conduit that do not experience any reconfigurations such as a Merge, Split, etc. So all the Driving Lanes within any given Lane Configuration Segment run along nicely next to each other without intruding into one another or splitting off or initiating or terminating. Each such Driving Lane component within a Lane Configuration Segment is called a "Lane Arrangement".



And each Lane Arrangement can be identified by either its inner or outer Lane Division since any given Lane Division pairs only with its counterpart on the other side of its Lane. You can't do this with the Driving Lane itself since, over the course of a Road Segment the same Lane Division might alternate the opposing Lane Division it pairs with.

Identifiers

1. Inside division + LCS + Road segment
2. Outside division + LCS + Road segment

Attributes

(No non referential attributes)

Lane Division (LD)

A linear, longitudinal designation inside of a Road Segment and roughly parallel with its edges for the purposes of separating Lanes of various types is a Lane Division. The inner and outer boundaries of any given Lane are established by two surrounding Lane Divisions.

We equate Lane Divisions with painted lines or curb edges most of the time, though there are many other physical features of the driving environment that may be construed to form a Lane Division. This is especially true when inclement weather or other adverse conditions are present. Degraded pavement conditions, weather, construction and other visual impediments may obscure or completely hide lane markings. Nonetheless, drivers (both human and automated) are often able to divine an effective Lane Division with cues such as map information, visible traffic patterns and color contrasts detected in the road surface.

The far edge of the Road Segment, say where pavement becomes gravel, or where the gravel drops off may constitute a Lane Division. This makes it possible to define the edge of a Shoulder Lane, for example.

Paint color, continuation patterns, stripe width and doubling, reflectors, construction cones and other physical elements may be combined to convey separation, intrusion and passing rules. Much of this visual symbology is region specific. In the future, much of this information may also be signaled in ways that are non-visual and readable only by computers.

To further complicate matters, a painted lane stripe may be visible yet not be observed by traffic due to overriding conditions such as construction, police activity, a more recent and brighter superseding stripe or other reasons.

The recognition and interpretation of lane symbols is outside the scope of our domain. Here we concern ourselves only with the existence and final interpreted meaning of a Lane Division and not its physical manifestation. If a line of construction cones is interpreted as a no-passing two way traffic separator, this becomes a Lane Division just as if it were a yellow stripe.

Identifiers

1. ID + Road segment

Attributes

Opposing traffic

Traffic on each side of this division flows in opposite directions.

Type: Boolean

Temporary

A Lane Division may temporarily override any other existing markings. This could be the case with traffic cones or some other non-permanent barrier.

Type: Boolean

Width

The distance between the left and right sides of a stripe or other Lane Division designation. This can be anything from zero for an invisible division to 30 cm or so. The width may become significant when a Lane

Division is adjacent to a hard Median. If it becomes necessary for the Ego Vehicle to swerve to avoid an obstacle, we can take into account the distance between the innermost edge of the visible Lane Division to the hard boundary of the Median with an eye toward avoiding both, but knowing that there is some leeway for some intrusion. And it may be helpful to know how much space is marked in between Lanes as well for maneuvering purposes.

Type: Stripe Width `0..100 cm`

Position

This is the lateral distance away from the outermost Lane Division. The outermost Lane Division is always at 0.0 m with increasing distances moving toward the inside. The distance between any two adjacent Lane Divisions in the same Conduit defines the width of a Lane.

Type: Distance

Lateral Lane Boundary

This is a location where a Lane comes to a definitive start or end ahead of the Ego Vehicle. For a Driving Lane it may correspond to the point where it enters an Intersection. For a Non Driving Lane it could be an abrupt end anywhere in the Road. Exclusion Lanes, in particular, tend to start and end abruptly. Abrupt is relative to the concept of a Merge or a Fork where driver's are given time to adjust to the new lane configuration. In the case of Non Driving Lanes, there is rarely a need for such a gradual transition. But Driving or Non Driving Lanes do start and end at specific locations.

Identifiers

1. ID + Road segment

Lateral Lane boundaries are numbered uniquely within a Road Segment.

Attributes

Location

The distance ahead of the Ego Vehicle where the boundary is observed.

Type: Distance

Left Road Edge

Left and Right Edges are abstracted independently to provide a clear definition of Road and distinguish it from non-road areas such as parking lots.

Identifiers

1. Road segment + Side

Attributes

Side

(No non-referential attributes)

Median

Any contiguous area or volume marked off or obstructed between two opposing Paired Conduits in a Two Way Road Segment constitutes a Median. Common examples are parallel cement barriers, grassy areas enclosed by guard rails or curbs, grassy areas not enclosed by any barriers, water barrels or even just an elongated patch of diagonal stripes. The purpose of the Median is to prevent or at least discourage traffic from entering the enclosed area.

A Median should not be confused with an Exclusion Lane. An Exclusion Lane belongs to a specific Conduit whereas a Median separates Conduits.

Some Medians are informally referred to as “central reservations”.

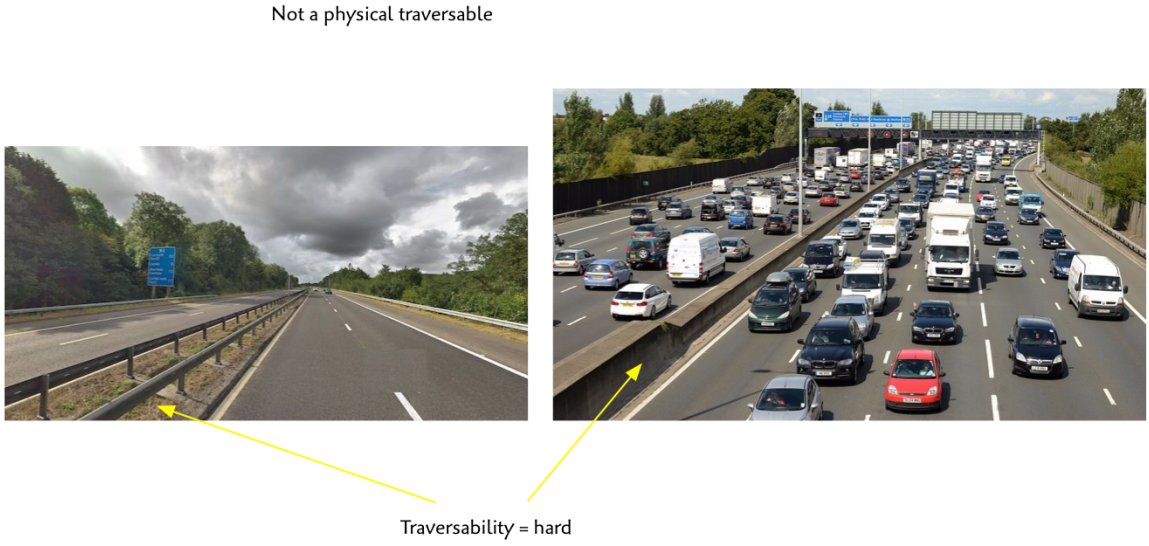
Identifiers

1. ID + Road segment

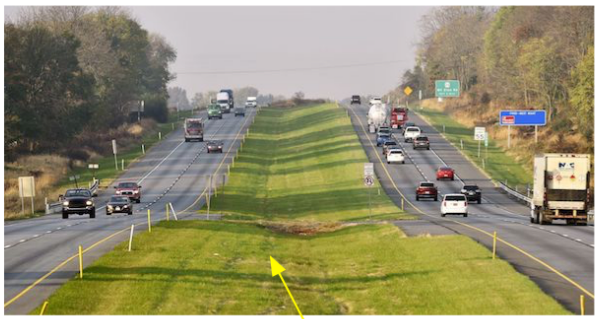
Attributes

Traversable

Is it possible to drive into the area enclosed by the Median? In case of an emergency, there may be utility in entering a traversable (open), or semi-traversable (soft) Median if there is adequate space. In some cases it may even be legal to park.



Grass median, not recommended, but possible



Traversability = soft

Traversable median in San Francisco Mission District (used illegally? for parking on Saturday night and Sunday morning!)

Traversability = open

Type: Traversability
[hard | soft | open]+

Width

The average distance between the inner Lane Divisions of each opposing Paired Conduit from the front of the Ego Vehicle up to a prescribed distance from the front of the Ego Vehicle or the part of the Median just before it slopes or curves to form the Median termination, whichever is nearest to the Ego Vehicle.

Type: Distance

Non Driving Lane

A Lane within a Conduit where ongoing vehicular traffic is either impossible or not permitted is a Non Driving Lane. Like all Lanes, these are longitudinally extended rectangular regions running parallel to the flow of vehicle traffic

A Non Driving Lane may be elevated, say at curb height, in which case it is an Exclusion Lane. The same is true if the Lane is not elevated, but occupied by a bus stop or otherwise painted to forbid or discourage entry.

A Dedicated Bike Lane might be crossed by vehicles, but it may not be driven in. (There are, of course, Driving Lanes which can be shared with cycle traffic to form non-dedicated bike sharing lanes, which are modeled as an aspect of a Driving Lane).

Shoulder Lanes are the other example where vehicles may not travel, though, depending on the regional rules and Lane Division properties, may be used for parking or circumvention. If a Shoulder is designated for temporary usage as a full fledged Driving Lane, it will be reclassified as such.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

(No non referential attributes)

One Way Road Segment

Traffic flows in only one direction via one or more Lanes in a One Way Road Segment.

Identifiers

1. ID

Attributes

(No non referential attributes)

Outside Shoulder

A Shoulder Lane on the outside of a Conduit.

Identifiers

1. Inside division + Outside division + Road segment

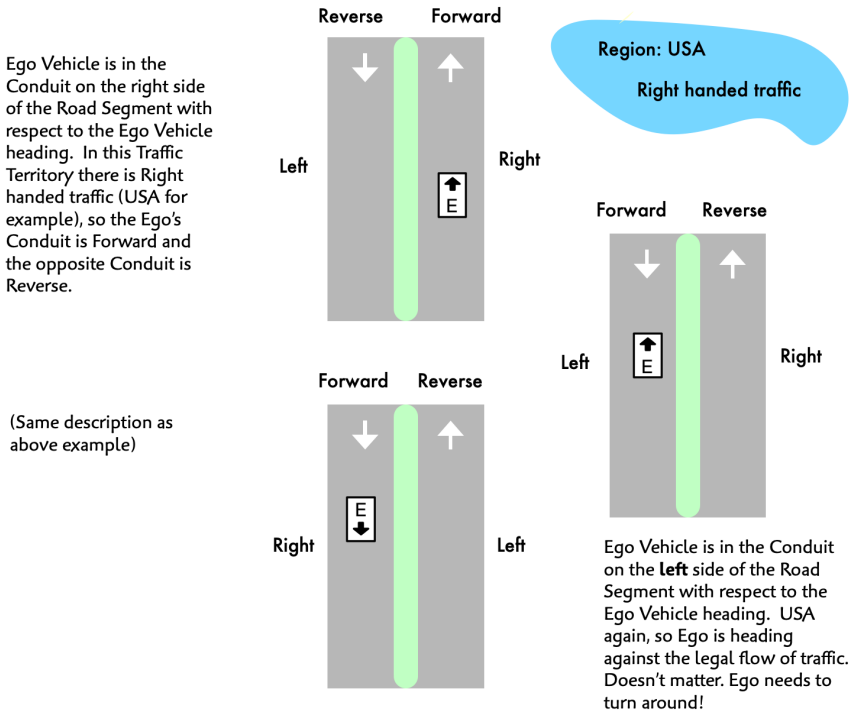
Attributes

(No non-referential attributes)

Paired Conduit

In two way traffic we have a Conduit flowing traffic one way and another Conduit flowing traffic in the opposite direction. Since both of these Conduits are adjacent to one another and describe the total flow of traffic on a Road Segment, we consider them to be paired.

Determining the direction of a Paired Conduit with respect to the regional traffic rule (right handed in this case) and the position (not heading) of the Ego Vehicle.



See the Road Segment description to see how left and right sides of the Road are determined for Roads crossing at various angles with respect to the Ego Vehicle's location and heading.

Identifiers

1. Road segment + Orientation

In a Two Way Road Segment, RS1 let's say, we'll see two Conduits: RS1-F and RS1-R. So we can easily tell them apart using these two components.

Attributes

Orientation

The choice of subclass, Forward Paired or Reverse Paired is determined with respect to the Ego Vehicle's current Conduit (which is always forward regardless of the Ego Vehicle's momentary orientation, see Forward Paired Conduit description) or where the Ego Vehicle may proceed as it travels in the legal direction of traffic projected from its current position.

Type: `[ F | R ]` forward or reverse

Parking Lane

A longitudinal section of the road may be designated for parking. Typically this is the outermost lane up against the curb of an urban Road Segment. But not always. Sometimes vehicles can park on the innermost side or even in the middle.

Here are some examples:

As we can see, the overall geometry forms a standard rectangular lane shape just like any other lane. In fact, when no cars are parked, it is not uncommon for vehicles to use (possibly illegally) the area as a Shoulder or Driving Lane.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

Orientation

The orientation of a parked vehicle with respect to the Ego Vehicle before parking.

Type: Parking
[parallel | angled | orthogonal]+

Restricted Driving Lane

Any Driving Lane marked with signs or other symbols limiting the type of traffic permitted in that Lane to certain types of vehicles during particular time intervals is considered a Restricted Driving Lane. Bus, carpool, emergency vehicle and taxi lanes are common examples.

Identifiers

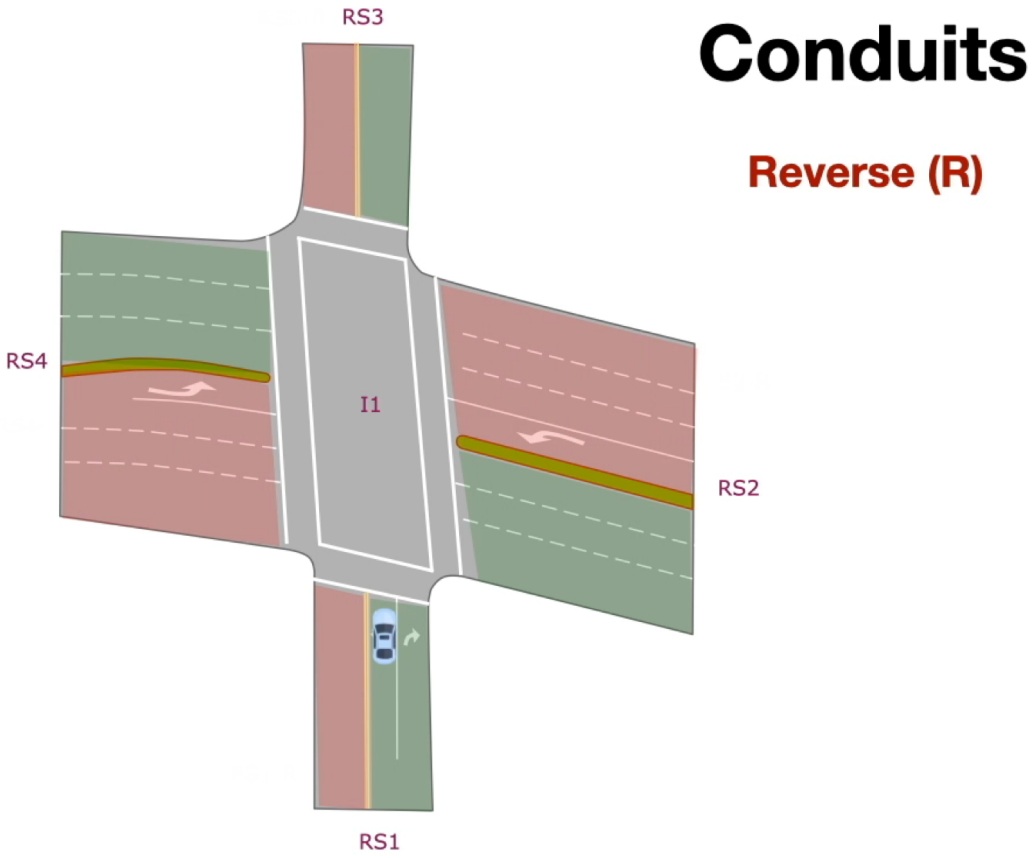
1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Reverse Paired Conduit

Any Conduit where traffic flows opposite of the legal flow of traffic in the Ego Vehicle's current Conduit.



Identifiers

1. Road segment

Attributes

(No non-referential attributes)

Right Road Edge

See description of Left Road Edge.

Identifiers

1. Road segment + Side

Attributes

(No non-referential attributes)

Road

In general parlance “road” can mean many things. It is largely because of the familiarity we all have with this term that makes it difficult to define precisely. For example, is an onramp a distinct road? Is a driveway? Are two adjacent and opposite flows of traffic a single road or two? Many definitions are possible, which is why we take our unique perspective into account.

In the Vehicle Environment domain, we take the perspective of the Ego Vehicle as it traverses and interacts with its immediate environment. Much of the time an Ego Vehicle will travel along some rectangular paved or otherwise treated surface in the long direction. The long direction of this rectangle will coincide with the Ego Vehicle heading when it is being traveled. Otherwise, the shorter width will be encountered typically at a right angle, but certainly from many other possible crossing, forking or merging angles.

Roads are typically named somehow. There may be a local designation such as “El Camino Real” or a more official, global name such as “CA-82”. These designations typically include both flows of traffic. So it seems natural to assume that a road may encompass either a unidirectional or bidirectional or possibly undirected flow of traffic. Most importantly, we can separate the concept of a flow of traffic in some direction from a road’s physical extent.

Whether or not it is immediately observable, we can say that a road is always bounded by two edges running lengthwise. One of the traverse edges begins on one detection horizon and on the roughly opposite horizon with respect to the Ego Vehicle.

Identifiers

1. ID

Attributes

ID

The Ego Vehicle may or may not be aware of the map name of the Road it is currently driving. So we use an arbitrary number to distinguish between “this road” and “that road over there”. But we always try to determine the correct Road Map Specification given our available navigational and sensory facilities.

Type: Road ID based on Nominal type

Road Edge

A Road Segment is defined as a drivable path with detectable right and left edges. If either or both Road Edge's are undetected, the vehicle could be in a parking lot or grass field environment where none of the road structure rules apply. So it is important to acquire both Road Edges (either through detection, map or assumption) before attempting to apply road rules.

Each Road Edge will coincide with an innermost or outermost Lane Division.

Identifiers

1. Road segment + Side

Attributes

Side

The side of the Road Segment from the perspective of the Ego Vehicle's forward direction when it is oriented in the legal direction of traffic. This means that if, for some reason, the Ego Vehicle is pointed in the wrong way direction, the Road Edge that you see to the right looking out of the front windshield is, in fact, the left edge of the Road. (That is, in fact, a good sign that you are pointed the wrong way!)

Type: Left Right
[left | right]+

Road Map Specification

This is the cartographical designation of a Road. With the help of road maps, you can correlate each Road observed by the Ego Vehicle with one of the mapped road names.

Identifiers

1. **Map name + Territory + Country**

Official names are chosen as to uniquely identify a Road within a Traffic Territory

Attributes

Map name

This is the official designation of the Road by the Traffic Territory. In many cases it will be identical to the local road name.

Type: Map Designation (such as “CA-1”, “CA-82”)

Local name

In many cases a road is shown on a map with a less formal name or sometimes known locally by a different name. This name is not guaranteed to be unique within its Traffic Territory.

Question: Could there be more than one unofficial name?

Type: Local Road Name (such as “Hwy 1”, “El Camino Real”, “Cabrillo Highway”)

Usage category

This describes the overall physical structure and the intended usage of a Road.

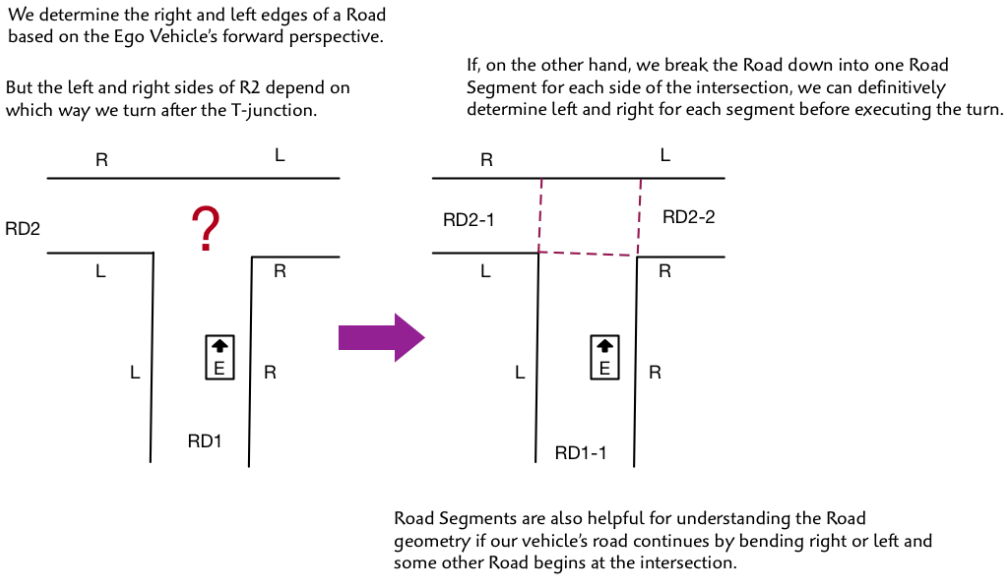
Note: If there is no definitive set of categories, we may need to abstract this out as a modeled class instead of using an enumerated type.

Type: Road Usage Category +
[no category | frontage | 2-1 | interstate | freeway | . . .]+

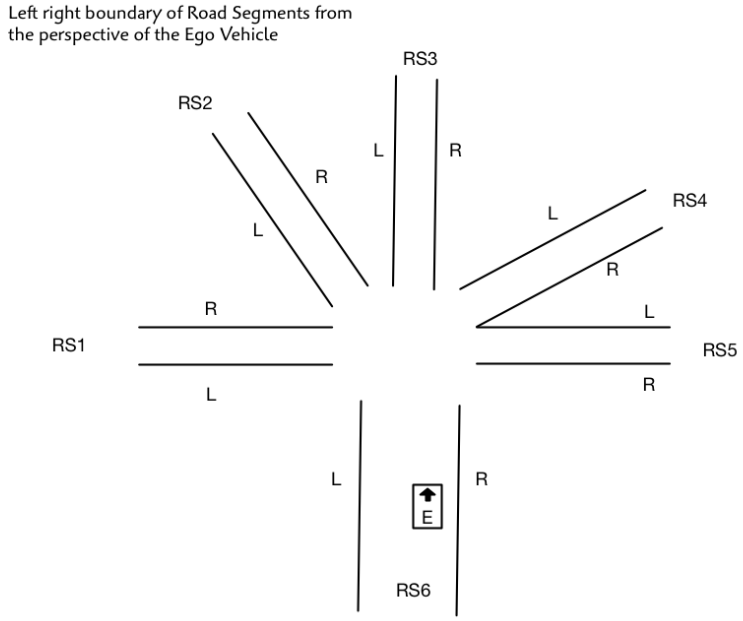
Road Segment

A chunk of road uninterrupted by any Intersection or Road departure is a Road Segment. This means that at an upcoming Intersection, the Ego Vehicle's Road Segment will end and one or more other Road Segments will emerge from each Intersection outlet.

This abstraction is necessary so that we can establish the left and right sides of the Road from the perspective of the Ego Vehicle. Without Road Segments we could reach contradictory answers. Consider the example below:



From the perspective of an Ego Vehicle facing multiple forking Roads, as shown below, Road Segments make it possible to establish clear left-right boundaries for all perceivable Roads.



Identifiers

1. ID

Attributes

ID

Each Road Segment is assigned a unique ID upon detection.

Type: Road ID based on Nominal type

Grade

The detected or marked grade of this Road Segment indicating its slope immediately up ahead.

Type: Road Grade

Pavement

The category of surface material detected immediately up ahead.

Note: The Lane Reconfiguration Subsystem will capture distances further ahead where there are changes in the surface material as well as other sequential changes to Road Segment properties.

Type: Surface Material

Condition

The overall quality of the surface.

Type: Surface Condition

Width

The average distance between the left and right boundaries from the front of the Ego Vehicle to some predetermined distance forward.

Type: Distance

Weathering

The effect of weather on the road surface such as icy, wet, dry and so forth.

Type: Surface Weather

Shared Road Segment

A strip of pavement where traffic is allowed to flow in either direction. Effectively, it has a single shared Lane where opposing traffic maneuvers carefully by veering to the side of the road and possibly stopping to avoid collisions.

Identifiers

1. ID

Attributes

(No non-referential attributes)

Shared Single Road Lane

There are no indicated Lane Boundaries on a Shared Road and traffic may pass in either direction. This is generally the case with a Road that is too narrow to accommodate two distinct lanes of traffic where two way traffic is permitted.

Here's an example in the country:

And here's a city example:

Identifiers

1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Shoulder Lane

From wikipedia:

```
_A shoulder is an emergency stopping lane by the verge of a road or  ↩
    motorway, on the right in countries which drive on the right, or  ↩
    on the left side in India, Japan, the UK, Australia, and other  ↩
    left-side driving countries. Many wider US and Swedish freeways  ↩
    have shoulders on both sides of each directional carriageway, in  ↩
    the median as well as at the outer edges of the road, for  ↩
    additional safety. Shoulders are not intended for use by through  ↩
    traffic, although there are exceptions._
```

This largely holds true in our model especially with the term “carriageway” replaced with Conduit.

That last sentence of the Wikipedia description refers to the temporary repurposing of a shoulder during heavy traffic as a normal driving lane. In this situation we rely on a lower layer of classification to determine this usage and then we’ll reclassify the observed Shoulder Lane as an Unrestricted Driving Lane. (So there is no need for a specialization of Shoulder Lane).

Identifiers

1. Inside division + Outside division + Road segment

Attributes

Quality

Shoulder Lanes are classified for usage by the type of underlying pavement. While each Lane is characterized by some type of pavement and surface condition, we can summarize the usability of a Shoulder Lane in more general terms.

Type: Shoulder Quality
[hard | soft]+

Soft Division Transition

A Soft Division Transition marks the beginning of a non-barrier portion of a Land Division. This happens when a Hard Division Transition ends with no further barrier or when a non-barrier Land Division comes into existence.

Identifiers

1. **ID + Division + Road segment**

Attributes

Passing ok

Traffic to the inside of this Lane Division may traverse across it for the purpose of overtaking a vehicle immediately in front of the Ego Vehicle.

Type: Boolean

Crossing ok

Traffic may laterally traverse this Lane Division for the purpose of turning or crossing the Road Segment.

Type: Boolean

Start of Lane

The location up ahead where a new Lane begins. Think of it as a Lane width line segment parallel to the front of the Ego Vehicle at some distance ahead.

For example, the Ego Vehicle might be approaching or traversing through an Intersection with the intent of going straight through. On the other side of the Intersection a new Road Segment begins along with a Start of Lane for each Lane in the forward Conduit.

Identifiers

1. ID + Road segment

Lateral Lane boundaries are numbered uniquely within a Road Segment.

Attributes

(No non-referential attributes)

Traffic Territory

This is a contiguous area within a Country that defines a set of uniform traffic policies. Chief among these is the left or right handedness of the traffic flow.

You might assume that the side that you drive on is determined by Country, but this is not always the case. Gibraltar, for example, is a British overseas territory were they drive on the right side of the road!

Note: We could tweak the meaning of Country to include Gibraltar as a distinct instance. But can we apply that trick everywhere in the world? Rather than worry about that, it is easier to just abstract Country and Traffic Territory separately with the common case being that they are one and the same.

Identifiers

1. Name + Country

Attributes

Name

This is a descriptive name for the purpose of unique identification within a Country. “Virgin Islands” for example.

Type: Territory Name

Traffic Orientation

Defines the flow of traffic within the entire Traffic Region. In the continental USA traffic is right handed but in the US controlled Virgin Islands, traffic is left handed.

Type: Side
[left | right]+

Two Way Road Segment

Traffic flows in two directions with each flow in its own Paired Conduit.

Identifiers

1. ID

Attributes

(No non referential attributes)

Unidirectional Lane

Any Lane that is part of a Conduit is considered unidirectional taking on the flow direction associated with its Conduit. This includes any Lane which forbids or discourages traffic, such as an Exclusion Lane.

Identifiers

1. Inside division + Outside division + Road segment
2. Inside division + Outside division + Conduit + Road segment

I2: A super-identifier (reducible identifier) is created by adding Conduit as a component. I1 would be enough to tell one Unidirectional Lane apart from another. In I2 we add Conduit and still get the same result. We do this because we need Conduit as a component of the Driving Lane Order class via R29 so that we can number Driving Lanes properly via OR34. See the OR34 relationship description for more details.

Attributes

(No non-referential attributes)

Unpaired Conduit

Traffic allowed to flow in only one direction without any adjacent opposing flow counterpart is abstracted as an Unpaired Conduit.

This situation happens frequently in urban traffic patterns where a street or alley is dedicated to a single direction of traffic. Counterpart streets that permit the opposing flow are typically scattered around the city, but, from the Ego Vehicle's perspective there is often no obvious correspondence. Thus, we characterize the traffic flow in isolated streets as Unpaired Conduits.

If, however, two streets are bound together tightly or with a Median, they will be characterized as Paired Conduits.

Identifiers

1. Road segment + Orientation

In a Two Way Road Segment, RS1 let's say, we'll see two Conduits: RS1-F and RS1-R. So we can easily tell them apart using these two components.

Attributes

Orientation

The choice of subclass, Forward Paired or Reverse Paired is determined with respect to the Ego Vehicle's current Conduit (which is always forward regardless of the Ego Vehicle's momentary orientation, see Forward Paired Conduit description) or where the Ego Vehicle may proceed as it travels in the legal direction of traffic projected from its current position.

Type: `[ F | R ]` forward or reverse

Unrestricted Driving Lane

A Driving Lane without any signs or markings limiting usage to certain vehicle types possibly during certain time intervals is an Unrestricted Driving Lane. If the Lane in which you are driving is not a bus lane, carpool lane or taxi only lane, it is probably unrestricted.

Even though the restrictions on a Lane may not be active at the moment, their mere specification establishes a Lane as restricted.

Identifiers

1. Inside division + Outside division + Road segment

Attributes

(No non-referential attributes)

Relationships

R1 / 1:M

- **Road** splits across intersections into *one or many* **Road Segment**
- **Road Segment** is stretch between intersections in *one* **Road**

Picture the driver's perspective looking out the front windshield of the Ego Vehicle. The Road lies ahead with clear left and right boundaries. Now we see another Road up ahead crossing ours at an oblique angle. This Road also has left and right boundaries, but from what perspective?

As always, we take the Ego Vehicle perspective. So, if we were to turn at the next intersection, onto this angled road, how would the boundaries of that road align? If we turn right, assuming two way crossing traffic, we have the nearest boundary on our right and the furthest on the left. Turning left, just the opposite.

If we approach an intersection and continue straight through, remaining on the same map road (CA-82) let's say, we enter a new Road Segment, but retain the same alignment with respect to the Ego Vehicle. So, re-orientation may or may not result in a new alignment of left/right boundaries.

Normally, a map road will continue straight through an Intersection. But many times continuing straight through an Intersection puts the Ego Vehicle on a different Road. To continue on the same Road, it may be necessary to take a left or right turn at the Intersection.

For both potential re-alignment of left/right boundaries and establishing what actual map Road the Ego Vehicle is on, it is helpful to abstract the notion of Road Segments.

In the case where an Ego Vehicle is traveling straight ahead on a single path of asphalt with no parallel or crossing paths, the Ego Vehicle is on a single Road consisting of only one Road Segment.

When a crossing road is observed connecting at an Intersection ahead, a Road Segment is seen on each interface to the Intersection. If traveling straight ahead, through the Intersection, the Ego Vehicle will leave one Road Segment and enter another on the other side. These two Road Segments may or may not belong to the same Road. They won't if the map road turns left or right instead of continuing straight.

A Road Segment is always part of a single Road. If, for some reason, map information is unavailable, temporary assumptions can be made about which Road a Road Segment belongs to.

In the world of maps, roads exist all the time, but from the Ego Vehicle's perspective, a Road is defined by observable Road Segments and cannot exist without at least one.

Formalization

Road Segment.Road $\rightarrow$ Road.Name

R2 / 1:1

- **Two Way Road Segment** has forward flow of traffic defined by *one* **Forward Paired Conduit**
- **Forward Paired Conduit** defines forward flow of traffic on *one* **Two Way Road Segment**

By itself, a Two Road Segment is just a strip of pavement, maybe with a Median in the center. The Forward Paired Conduit is the rule that all traffic must flow in one direction within one or more adjacent Lanes. So we are pairing a physical structure (the Road Segment) with a policy (Conduit).

The assignment of forward and reverse depends on the location of the Ego Vehicle. See the Forward Paired Conduit class description for a more detailed explanation.

Formalization

Forward Paired Conduit.Road segment → Two Way Road Segment.ID

R3 / is a

- **Road Segment** *is a* **One Way**, **Two Way** *or* **Undivided Road Segment**

There are only three possible ways that traffic can flow on a Road Segment. Traffic either flows one way, both ways divided or both ways undivided.

Formalization

<subclass>.ID → Road Segment.ID

R4 / 1:1

- **Two Way Road Segment** has reverse flow of traffic defined by *one* **Reverse Paired Conduit**
- **Reverse Paired Conduit** defines reverse flow of traffic on *one* **Two Way Road Segment**

See the description for R2.

Formalization

Reverse Paired Conduit.Road segment -\> Two Way Road Segment.ID

R5 / 1:1

- **One Way Road Segment** has single flow of traffic defined by *one* **Unpaired Conduit**
- **Unpaired Conduit** defines single flow of traffic on *one* **One Way Road Segment**

By itself, a One Road Segment is just a strip of pavement. The Unpaired Conduit is the rule that all traffic must flow in one direction within one or more adjacent Lanes on that pavement. So we are pairing a physical structure (the Road Segment) with a policy (Conduit).

Formalization

Unpaired Conduit.Road segment → One Way Road Segment.ID

R6 / is a

- **Paired Conduit** *is a* **Forward** *or* **Reverse Paired Conduit**

The purpose of a Paired Conduit is to define a two way flow of traffic with a Conduit establishing each opposing direction.

Formalization

<subclass>.Road segment → Paired Conduit.Road segment

R7 / is a

- **Conduit** *is a* **Paired** *or* **Unpaired Conduit**

A Conduit is either used as part of a two-way pair, in which case it is Paired, or it defines one-way traffic in which a single, unpaired Conduit suffices.

Comment: This works nicely until we consider cases where one pair of Conduits is sandwiched inside of another Pair as happens in freeway interchange feeders. The "Toronto Basketweave" is an extreme case in point. But we need only look at the I280/SR-1 interchange in South San Francisco, CA, USA for an example. The definitions may still hold if we have a good model that explains freeway feeder patterns, which we do not currently have. All that said, we need a clear set of rules since the idea of just grouping Conduits arbitrarily is certainly not a solution that accurately characterizes the real world!

Formalization

<subclass>.Road segment → Conduit.Road segment

R8 / 1:Mc

- **Road** driving side is established by *one* **Traffic Territory**
- **Traffic Territory** establishes driving side of *zero, one or many* **Road**

You may or may not know what Road you are driving on, but you must always know which Traffic Territory you are in so that you know which side of the Road to drive on. Keep in mind that you can always observe oncoming traffic if you aren't sure, take into account the rough estimate of where you are in the world and make a good guess as to which Traffic Territory you must be in, so this is not an unreasonable requirement. Therefore, the Traffic Territory is presumed to always be known.

A given Traffic Territory certainly establishes the driving side of all Roads it contains. There has to be at least one or it breaks the definition of being a Traffic Territory.

Formalization

Road.(Traffic territory, Country) → Traffic Territory.(Name, Country)

R9 / 1:M

- **Conduit** flows traffic through *one or many* **Unidirectional Lane**
- **Unidirectional Lane** is a partial flow of traffic in *one* **Conduit**

By definition, a Conduit is a flow of traffic in one direction. It is a collection of adjacent Unidirectional Lanes all flowing traffic in the same direction.

Formalization

Unidirectional Lane.(Conduit role, Road segment) → Conduit.(Role, Road segment)

R10 / is a

- **Unidirectional Lane** *is a* **Driving** *or* **Non Driving Lane**

The Lanes in a Conduit can serve various purposes. There is a primary distinction between the Lanes where it is permitted to travel (drive forward indefinitely) and those where driving is either entirely forbidden or permitted only for temporary occupation for specific maneuvers.

Formalization

<subclass>.(Inside division, Outside division, Road segment) → Unidirectional Lane. (Inside division, Outside division, Road segment)

R11 / is a

- **Driving Lane** *is a* **Restricted** *or* **Unrestricted Driving Lane**

You could make the argument that all Driving Lanes are restricted in some way with a complete lack of restrictions being the simple case. In practical usage, though, most Driving Lanes are unrestricted with restrictions being the exception. It makes sense to separate out the case where special attention must be applied just as humans do when they drive normally.

Formalization

<subclass>.(Inside division, Outside division, Road segment) → Driving Lane.(Inside division, Outside division, Road segment)

R12 / 1:Mc

- **Flow Separator** physically separates opposing traffic flow in *one* **Two Way Road Segment**
- **Two Way Road Segment** has opposing traffic flow separated physically by *zero, one or many* **Flow Separator**

A Flow Separator exists between opposing traffic when there is some kind of visual or physical barrier significantly wider than a painted line. This barrier is either a Median which may or may not be physically traversable or it is a Center Turn Lane.

Multiple different Flow Separators may be observed simultaneously on the same Two Way Road Segment. For example, an island Median may narrow to a single striped line and then widen back out to another Median without any intervening Intersection. Or, see Flow Separator for an example where a Median is situated between two Center Turn Lanes on the same Two Way Road Segment.

When there is nothing more than a striped line in between two opposing flows of traffic, there is no real physical Flow Separator.

Formalization

Flow Separator.Road segment → Two Way Road Segment.ID

R13 / is a

- **Flow Separator** *is a* **Center Turn Lane** *or* **Median**

These are only two known uses of the space between opposing Paired Conduits in a Two Way Road Segment. It's always possible that some other usage exists outside the USA and if one is found, we may need to revise this relationship.

Formalization

<subclass>.(ID, Road segment) → Flow Separator. (ID, Road segment)

R14 / is a

- **Division Transition** *is a* **Soft** *or* **Hard Transition**

The boundary between two Lanes is either an easily traversable painted or otherwise marked line or it is a physical boundary such as a cement barrier which may or may not also have a marked line alongside it. The key distinction here is whether or not it is physically possible to traverse the Lane Division without incurring serious damage.

For a soft (traverseable) Division Transition, there may be a variable crossing policy. When there is only paint on the road, there is always the option, legal or illegal of driving across the paint. For a Hard Transition,

some sort of physical barrier is in place. In all such cases, there is no option since traversal is physically discouraged and therefore certainly illegal.

All Division Transitions serve the purpose of defining the condition of a Lane Division extending forward from some position with respect to the Ego Vehicle.

Formalization

<subclass>.(ID, Division, Road segment) → Division Transition. (ID, Division, Road segment)

R15 / is a

- **Road Edge** *is a* **Left** *or* **Right Road Edge**

Since an edge is defined as the longitudinal sides of a rectangular area, these are the only geometric possibilities.

Formalization

<subclass>.Road segment → Road Edge.Road segment

R16 / is a

- **Non Driving Lane** *is a* **Shoulder**, **Dedicated Bike**, **Parking** *or* **Exclusion Lane**

These appear to be all of the types of Lanes in a Conduit that exclude normal vehicle travel. There are, of course, many special purpose lanes such as carpool, bus only and so forth, but these are covered as Restricted Driving Lanes as travel is allowed there, but it is restricted by usage.

Formalization

<subclass>.(Inside division, Outside division, Road segment) → Non Driving Lane. (Inside division, Outside division, Road segment)

R17 / 1:1

- **Shared Single Road Lane** constrains traffic flowing in opposite directions on *one* **Shared Road Segment**
- **Shared Road Segment** flows opposing traffic both ways in *one* **Shared Single Road Lane**

When a road has a single lane, is there really a lane at all? The main purpose of lanes is to separate traffic via physical or marked boundaries. It is certainly the case that a Shared Road Segment might have markings or physical boundaries on the left or right. These are coincident with the Road Edges and Road Edges are defined by the extreme Lane Divisions.

So, yes, even the minimal case of a Shared Road Segment does require a Lane.

By definition, a Shared Single Road Lane must be laid out on a Shared Road Segment.

Formalization

Shared Single Road Lane.Road segment → Shared Road Segment.ID

R18 / is a

- **Bidirectional Lane** *is a* **Shared Single Road Lane** *or* **Center Turn Lane**

Two way traffic in a single Lane is inherently dangerous. Consequently, there must be very few cases where this is allowed. In fact, only two are known at this point. Either the road lacks a Conduit and there is no designated traffic direction or a special lane is designated for making turns across the roadway where traffic can approach from either direction.

Formalization

<subclass>. (Inside division, Outside division, Road segment) → Bidirectional Lane. (Inside division, Outside division, Road segment)

R19 / is a

- **Lane** *is a* **Unidirectional** *or* **Bidirectional Lane**

A Lane either constrains traffic to legally flow in one direction or it allows traffic to move in either direction. Bidirectional traffic is permitted when a Road consists of only one Shared Road Lane or when a Shared Turn Lane is sandwiched between the Conduits in a Two Way Road Segment.

Formalization

<subclass>. (Inside division, Outside division, Road segment) → Lane. (Inside division, Outside division, Road segment)

R20 / 1:M

- **Road Segment** traffic is separated by *one or many* **Lane Division**
- **Lane Division** separates traffic on *one* **Road Segment**

Every Road Segment is divided up into Lanes indicated by Lane Divisions. In the case of an Undivided Road Segment, there will be at least an inside and outside division corresponding, roughly at least, to the left and right Road Edges even if they are not explicitly marked.

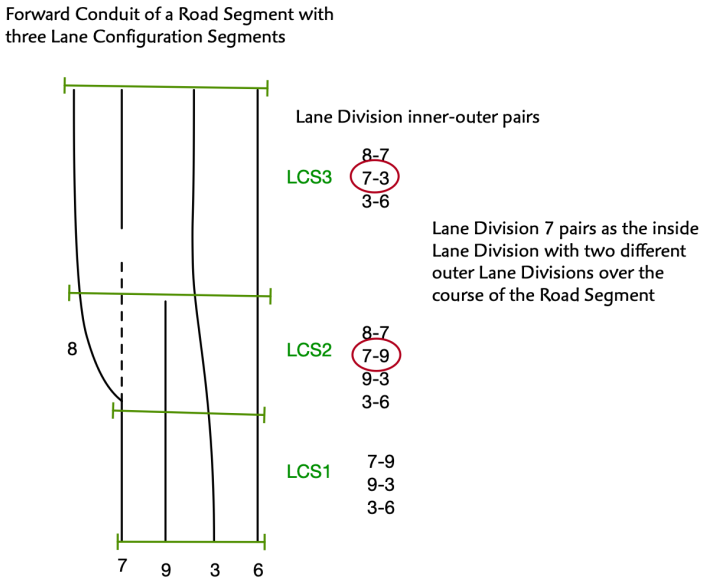
Formalization

Lane Division.Road segment → Road Segment.ID

R21 / M:M-1

- **Lane Division** is toward the outside/inside of *one or many* **Lane Division**

A Lane Division is defined as the space between two adjacent Lane Divisions. This suggests a 1:1 relationship or inner-outer pairing of Lane Divisions. But if you look at the full length of a Road Segment (see below) it is apparent that the same Lane Division may pair with different Lane Divisions as the lanes are reconfigured.



For any pair of adjacent Lane Divisions on a Road Segment, one division will be toward the inside (nearest the Median) and the other toward the outside (nearest the shoulder). See Lane.Inside division description for more about the use of inside/outside directions.

The innermost Lane Division will not be outside of any other Lane Division and the outermost Lane Division will not be inside any Land Division, hence the conditionality (zero multiplicity case).

Formalization

Lane.(Inside division, Road segment) → Lane Division.(ID, Road segment) Lane.(Outside division, Road segment) → Lane Division.(ID, Road segment)

R22 / 1:M

- **Road Segment** has traffic organized by one or many **Lane Division**
- **Lane Division** organizes traffic for one **Road Segment**

Road traffic always flows in Lanes so there must be at least one Lane (and hence two Lane Divisions) on each Road Segment.

Formalization

Lane.Road segment → Lane division.Road segment

R23 / 1:1

- **Right Road Edge** bounds right side of *one* **Road**
- **Road** is bounded on right side by *one* **Right Road Edge**

By definition, a Road Segment has a left and right Road Edge.

Formalization

Right Road Edge.Road segment → Road Segment.ID

R24 / 1:1

- **Left Road Edge** bounds left side of *one* **Road**
- **Road** is bounded on left side by *one* **Left Road Edge**

Similar to R23, but on the left

Formalization

Left Road Edge.Road segment → Road Segment.ID

R25 / 1:Mc

- **Exclusion Lane** encloses *zero, one or many* **Island**
- **Island** is enclosed in *one* **Exclusion Lane**

Any number of Islands (separated by longitudinal space) may be observable in the same Exclusion Lane. If an Exclusion Lane is simply marked by paint, there will be no Island at all.

An Island, by definition, exists only within an Exclusion Lane.

Formalization

Island. (Inside division, Outside division, Road segment) → Exclusion Lane. (Inside division, Outside division, Road segment)

R26 / 1:1c

- **Lane** begins at *zero or one* **Start of Lane**
- **Start of Lane** is beginning of *one* **Lane**

If a Start of Lane is observed, it must, by definition, be the start of some Lane.

As the Ego Vehicle travels alongside a Lane, it may or may not be able to detect the Start of the Lane as it could be several kilometers behind.

Formalization

Start of Lane.(Inside division, Outside division, Road segment) → Lane.(Inside division, Outside division, Road segment)

R27 / 1:1c

- **Lane** terminates at *zero or one* **Start of Lane**
- **Start of Lane** is termination of *one* **Lane**

Same logic as R26.

Formalization

End of Lane.(Inside division, Outside division, Road segment) → Lane.(Inside division, Outside division, Road segment)

R28 / is a

- **Lateral Lane Boundary** *is a* **Start** *or* **End of Lane**

The abstraction of Start and End of Lane subclasses makes it possible to state that, at any point in time from the perspective of the Ego Vehicle, either, both or none may be visible.

Formalization

<subclass>.(ID, Road segment) → Lateral Lane Boundary.(ID, Road segment)

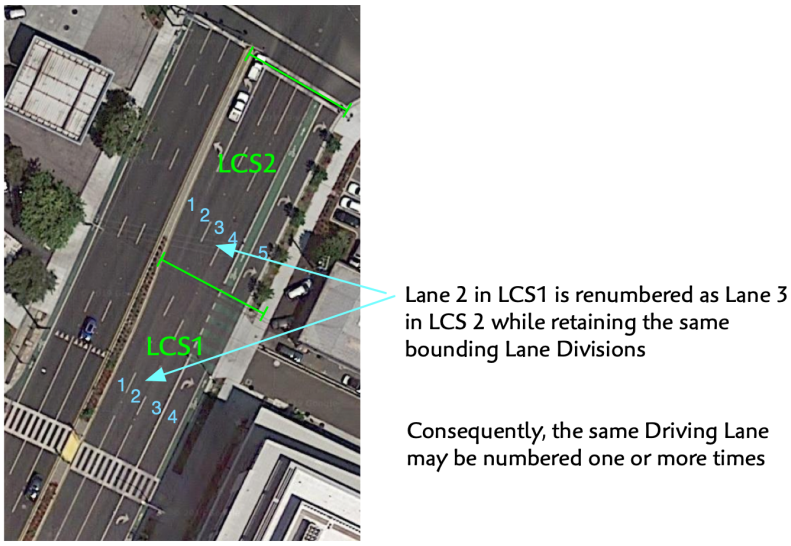
R29 / 1c:M-1

- **Lane Arrangement** numbers *zero or one* **Driving Lane**
- **Driving Lane** is numbered according to its *one or many* **Lane Arrangement**

If a Lane Arrangement partitions a Driving Lane, not a Dedicated Bike Lane for example, it is used to number its Lane using the California lane numbering system.

As a Driving Lane progresses through its Conduit, it will span one or more Lane Configuration Segments. Each such span yields a distinct Lane Arrangement and a potentially different California style lane number.

Within a Lane Configuration Segment, no Driving Lanes are reconfigured. If any Merge, Fork or other reconfiguration is initiated, a new Lane Configuration Segment begins and all the lanes are renumbered (not the Lane Divisions, but the Driving Lanes themselves according to the California numbering scheme). Here is an example:



Lane reconfiguration and Driving Lane numbering are relevant only to Driving Lanes, so a Lane Configuration Segment is defined only when there is at least one Driving Lane present in the Road Segment. By contrast, a Shared Single Road Lane, has no Driving Lane and, hence no lane reconfiguration.

Every Driving Lane longitudinally spans at least one Lane Configuration Segment. This is because every Driving Lane is initiated at some point and Driving Lane Initiation is defined in the Lane Reconfiguration Subsystem as some type of lane reconfiguration.

Note that Center Turn Lanes are not considered when defining Lane Configuration Segments. A Center Turn Lane runs between the opposing Conduits of a Road Segment and is subject to lane initiation and termination. Furthermore, Center Turn Lanes are not numbered using the 1, 2, 3 lane numbering system.

Formalization

Driving Lane Order.(Inside division, Outside division, Road segment) → Driving Lane.(Inside division, Outside division, Road segment) Driving Lane Order.(Inside division, LCS, Road segment) → Lane Arrangement.(Inside division, LCS, Conduit, Road segment)

Additional constraints

Driving Lane Order.(Outside division, LCS, Road segment) → Lane Arrangement.(Outside division, LCS, Road segment)

R30 / 1:M

- **Traffic Territory** defines orientation of traffic in *one* **Country**
- **Country** regulates traffic orientation by *one or many* **Traffic Territory**

Usually when we think about the direction of traffic flow (right vs. left handed) we imagine a particular Country. "We drive on the left in the UK", "We drive on the right in the USA". But this is actually not correct. The US controlled Virgin Islands, for example, are considered part of the USA, but the island traffic drives on the left. The UK includes Gibraltar where traffic is right handed due to proximity with Spain. Many Countries are covered by a single Traffic Region, and there must be at least one to define the direction of traffic.

A Traffic Region is defined entirely within the geographic boundaries of its Country. So, even if traffic rules are the same across multiple Countries, each will define its own Traffic Region.

Formalization

Traffic Region.Country → Country.Name

R31 / 1:M

- **Road Map Specification** is administered by *one* **Traffic Territory**
- **Traffic Territory** administers *one or many* **Road Map Specification**

The term "administration" refers to the rule-setting authority over a Road. So a given map road is managed by a single authority or Traffic Territory. Even though a road may appear to originate in one Country on a map and continue on into another, that road will, in fact, correspond to two distinct Road Map Specifications.

For example, Interstate 5 (I-5) changes to Highway 99 when it crosses into Canada even though it is a continuous stretch of pavement.

Formalization

Road Map Specification.(Territory, Country) → Traffic Territory.(Name, Country)

R32 / 1c:Mc-1

- **Road Map Specification** identifies *zero, one or many* **Road**
- **Road** is identified by *zero or one* **Road Map Specification**

A perceived Road may or may not be found on a map (identified by the mapping system) at a given point in time. If it is correlated, it must be with a single map designation. In case of doubt, there is no correlation.

It stands to reason that a Road Map Specification would name a single Road. But how could the same specification name multiple Roads?

Imagine the case when an exit diverges just up ahead of the Ego Vehicle, forming its own separate Road. Now let's say that the exit leads to a continuation of the same Road Map Specification.

Let's say, for example, that we are on SR-1 (California Highway 1) which merges onto I280 (Interstate 280), but the exit will keep us on HWY1. So now we have two perceived Roads (HWY1) which we are driving on, and HWY1 corresponding to the exit Road. (I280 is not yet detected, but will become the new designation of the current Road if we don't take the exit).

Comment: This all depends on how we defined Road transitions. In the above example, the Road we are on is continuous before and past the exit. So, as we drive past the exit, our Road is re-associated with a new Road Map Specification (from SR-1 to I280). The exit is a new Road (right and left edges) and is associated with SR-1. But, just before the exit, both Roads are associated with SR-1.

But let's say that we decide to model this another way. Maybe we break our Road into Road Segments before and after the exit. Well, that still doesn't help since they would presumably belong to the same Road. Or, we might say that the exit is not really SR-1. Perhaps an exit should have its own name such as 508A. In that case. We're going to have to do a thorough analysis of freeway interchanges before we're sure. For now, we'll leave this as a `0..1:1..*` *association pending further development of the model.*

Formalization

Known Map Road.Road → Road.ID Known Map Road.(Map name, Territory, Country) → Road Map Specification. (Map name, Territory, Country)

R33 / is a

- **Shoulder Lane** *is an* **Inside** *or* **Outside Shoulder**

Unlike other lanes, a Shoulder Lane can exist only on the left or right side of a Conduit. So, at most, there can be only two Shoulder Lane's per Conduit. Furthermore, the inner Shoulder Lane's Inner division must be the Conduit's innermost Lane Division. The outer Shoulder Lane's outer Lane Division must be the Conduit's outermost Lane Division.

Here is a single Road Segment with multiple Conduits, Lane Divisions, four Unrestricted Driving Lanes and four Shoulder Lanes

Shoulder Lanes

Road Segment	Conduit	Side	Inner division	Outer division
RS1	F	Inside	9	3
RS1	F	Outside	7	2
RS1	R	Inside	10	4
RS1	R	Outside	11	11

Note that you cannot have two Shoulder Lanes in a Conduit on the same Side since Side is part of an identifier on Shoulder Lane

Formalization

<subclass>.(Inside division, Outside division, Road segment) → Shoulder Lane.(Inside division, Outside division, Road segment)

OR34 / Ordinal

- **Driving Lane Order** outermost, innermost

Driving Lanes are numbered in ascending order starting with 1 for the innermost Driving Lane in a Conduit. Only Driving Lanes are numbered in this fashion, so Bike Lanes, Shoulders, etc. are excluded.

We number them uniquely (1, 2, 3. . .) within each Lane Configuration Segment.

Formalization

Driving Lane Order.Number *in* (LCS, Conduit, Road segment)

R36 / 1:M

- **Lane Division** changes at *one or many* **Division Transition**
- **Division Transition** is change in *one* **Lane Division**

As you drive along looking up ahead you can see the Lane Divisions changing. A dashed line turns solid, a solid line starts running along a curbed median with trees and so forth.

The current Driving Transition constitutes the status of a Lane Division alongside the Ego Vehicle. So if you see a dashed line to your left, that represents the current or zero distance Driving Transition. So, if there is a Lane Division there, it must have at least one Driving Transition at a zero distance. In other words, there is always a current Driving Transition for each Lane Division.

Additionally, you may see one or more transitions up ahead where the Lane Division changes physical structure, crossing policy or both.

Any given Division Transition represents the status of a single Lane Division.

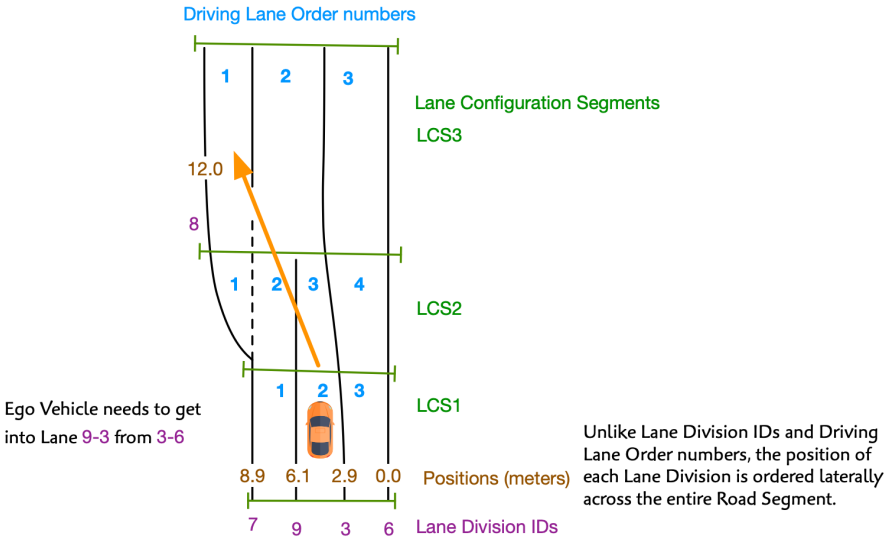
Formalization

Division Transition.(Division, Road segment) → Lane Division.(ID, Road segment)

OR37 / Ordinal

Lane Division outermost, innermost

When we look down the Road Segment ahead, we see a number of Lane Divisions starting with an innermost Lane Division progressing to an outermost Lane Division. Our Lane Division IDs are not ordered, so from outermost to innermost near our vehicle we see 6,3,9,7. Further up, two lanes merge (7-9) and (9-3) to form (7-3) and an inside turn lane forks to form (8-7).



If we want to get into (8-7) to make the inside turn, how do we know which Lane Division to cross first? We need a way to determine that (8-7) is to our inside. Since the Lane Division IDs are not ordered, so we can't use them to figure it out. We also have the problem that (8-7) isn't even in our current Lane Configuration Segment. Driving Lane Order numbers (Lane 1, Lane 2, etc) don't work either since they vary by Lane Configuration Segment. What we need is a total lateral position ordering of Lane Divisions across the entire Road Segment (irrespective of Lane Configuration Segments).

Fortunately, the Position (lateral distance) of each Lane Division give us just that. Even though actual distances may vary as lanes narrow and widen by small amounts, Lane Divisions never cross over each other! So we can always use the position ordering to determine whether we need to move to the inside or outside to reach our objective Driving Lane.

Formalization

Driving Lane Order.Number *in* Road segment

R39 / 1:1c

- **Outside Shoulder** is on the inside of *one* **Conduit**
- **Conduit** has on inside *zero or one* **Outside Shoulder**

See R38 description.

Formalization

Outside Shoulder.(Conduit, Road segment) → Conduit.(Side, Road segment)

R40 / M:M-1

- **Unidirectional Lane** is arranged within *one or many* **Lane Configuration Segment**
- **Lane Configuration Segment** arranges *one or many* **Unidirectional Lane**

In the simplest case, a Conduit in a Road Segment will consist of one or more Unidirectional Lanes that do not experience any reconfiguration. In this case, the entire Conduit will be covered by a single Lane Configuration Segment.

Each Unidirectional Lane runs through at least this single Lane Configuration Segment. If the lanes are reconfigured, there will be more than one Lane Configuration Segment to organize the reconfigurations.

Formalization

Lane Arrangement.(Inside division, Outside division, Conduit, Road segment) → Unidirectional Lane Lane Arrangement.(LCS, Road segment) → Lane Configuration Segment.(ID, Road segment)

R41 / 1:1c

- **Lane Division** marks *zero or one* **Road Edge**
- **Road Edge** is marked by *one* **Lane Division**

On any given Road Segment, there will be two Lane Divisions that each mark a Road Edge. Since there are always two Road Edges, there must always be two such Lane Divisions in the Road Segment.

Formalization

Road Edge.(Lane division, Road segment) → Lane Division.(ID, Road segment)

OR42 / Ordinal

Division Transition ascending from closest

Division Transitions are ordered for each Lane Division ascending from the closest to the furthest away from the Ego Vehicle by Location. This makes it possible to both determine the currently active transition as well as the upcoming transitions in sequence as the Ego Vehicle drives along.

Formalization

Division Transition.Location

Division Transition.Division

Division Transition.Road segment

Chapter 3

Methods

The third facet of a complete Executable UML model is a set of activities. Each activity specifies computation through a number of not-necessarily sequential actions.

(Sequencing may vary by implementation unless otherwise indicated in the activity. A data flow model of processing is assumed whereby each action may execute only when its inputs are available. Upstream actions are chained together to output data and/or control to downstream actions.)

A method is an activity defined on a class and is executable by any instance of that class.

Driving Lane Methods

Adjacent DL entry

Scrall

```
// Class method: Driving Lane
// ---
// Adjacent DL( direction : Inner Outer, lcs: Lane Configuration Segment ID  ↩
    ) : Lane Division ID[1c]
// ---

// Find the nearest adjacent Driving Lane, if any in the indicated direction
// Returns one or zero (1c) Lane Division ID


// Returns one or zero instance by following OR34 up or down one step in the
// specified direction and then selecting the associated Driving Lane
// If the specified Driving Lane is the inner most or outermost and moving  ↩
    in the
// same direction return the empty set

// We must choose the next lane over in the specified Lane Configuration  ↩
    Segment
```

```
in.direction == .inner?
    =>> /R29/OR34/descending/R29/Driving Lane( in.lcs )
    =>> /R29/OR34/ascending/R29/Driving Lane( in.lcs )
```

The main complication of the translation is to compute **OR34**. **OR34** is a total ordering on Driving Lane Order instances within the same LCS and Road Segment. The strategy is to first find the Driving Lane Order instance which is related to the current Driving Lane and in the same LCS as the input argument. That allows us to determine the value of the **Number** attribute. Depending upon the direction, the adjacent Driving Lane Order instance is either one more or one less than the Number of the found Driving Lane Order. However, we must take care of the boundary conditions. If you are all the way inside, *i.e.* the number is 1, then you can't go further inside and we fail to find an adjacent lane in that direction. Conversely, if your direction is toward the outer and you are already at the outer most lane, then there is no adjacent lane there either. Once a new value for the Number attribute is known, we can find the adjacent Driving Lane Order by performing a blind select on the Driving Lane instances looking for that instance which has the same LCS and Road segment, but with a Number value matching the adjacent lane. This approach is necessary because **OR34** is realized by Number, LCS, and Road Segment. There is no `micca` defined relationship for **OR34**, so there is no pointer reference which could be used for navigation. That selection may fail, which is OK, but if it succeeds, then we find the adjacent Driving Lane instance by traversing back across R29.

Traffic Territory Methods

Side conversion

Scrall

```
// Class method: Traffic Territory
// ---
// Side conversion ( direction: Inside Outside ) : Left Right
// ---
// Determine the local hand direction (left/right) for a value of inside or outside
// USA is .right with .inside direction being on the .left side
// Japan is .left with .inside direction being on the .right side
Traffic orientation? {
    .right : direction == .inside? =>> .left : =>> .right
    .left : direction == .inside? =>> .right : =>> .left
}
```

Part I

Reference Material

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