Ontologies and ODDs at Five

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24th April 2020

📌 Topics

- Five + Iain
- Importance of ODD/Operating Domain
- Our Approach
- A language for Ontologies
- Use Cases
- Requirements from Five

Team of 130 engineers and computer scientists focused on solving the hard problems in self-driving

Recognised the size of the task and the need for $ billions in capital to deliver safe self-driving services

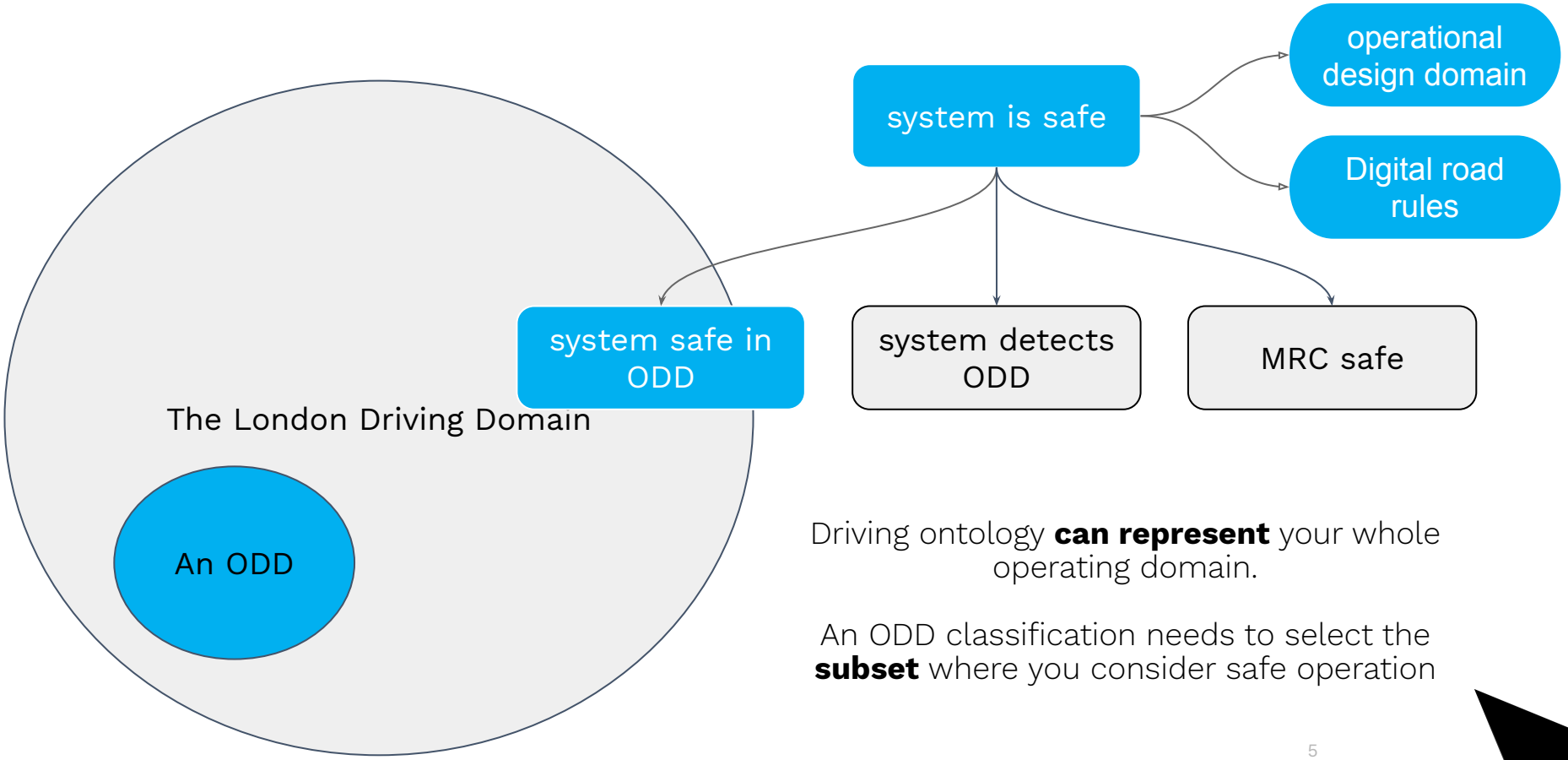
Built level 4 reference stack with UK government support and taken hundreds of test drives over 21km route in London during 2019

Closed $41M Series B (final tranche Feb 2020) based on pivot to **deliver key tech for V&V to firms** spending those billions

- Director of Assurance @ Five
- Prev. Safety and Robust Software @ NASA
- Prev. Formal Verification + DSLs and programming language semantics

ODD and Operating Domain

🙃Scope of an ontology



Driving ontology **can represent** your whole operating domain.

An ODD classification needs to select the **subset** where you consider safe operation

Our approach

5️⃣ Our approach

Coherent tooling for a formal ontology, with formal releases

Reference it formally and with traceability throughout company

Currently: hard-coded map between OpenX

Represent ODD, Road Rules, Scenarios using this language

Feed directly into into safety case: backbone for structure

Ontology

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WorldScene.ontology

```
five ai ontology specification WorldScene

class WorldScene : "The top level class for specifying the ODD-type scene for an EGO"
    attribute EgoState as EgoState
    attribute EnvironmentalState as EnvironmentalState
    attribute RoadStructure as RoadStructure
    attribute ActiveRoadState as ActiveRoadState
```

Version-controlled cloud-based Integrated Development Environment for specifying a driving domain ontology, ODDs, and “scenes” AKA scenarios in that domain ontology.

At the top level we have a “world scene”, which defines an instant snapshot of a scenario.

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```

Domain Specific Language for specifying ontology elements. A simplification of a fully-featured OWL language.

Completely customizable, though top-level is integrated with a scene language (more later).

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EnvironmentalState.ontology ×

```
five ai ontology specification EnvironmentalState

class EnvironmentalState : "The conditions associated with the state of the environment."
    attribute SkyCondition as SkyCondition
    attribute WeatherCondition as WeatherCondition
    attribute GroundCondition as GroundCondition
    optional attribute WindLevel as WindLevel default Calm
    optional attribute AirParticulateMatter as AirParticulateMatter default ClearAir


class WeatherCondition : "The types of weather that the Five AI Ontology distinguishes"
    values type = number range = [0,) units = "mm/h"
    class ClearCalm :: WeatherCondition : "Dry weather with little wind"
        values type = number range = [0,0] units = "mm/h"
    class AdverseConditions :: WeatherCondition : "Conditions that adversely affect the vehicle"
        class Snow :: AdverseConditions : "Snowing"
            values type = number range = (0,) units = "mm/h"
        class Sleet :: AdverseConditions : "Sleet Shower"
            values type = number range = (0,) units = "mm/h"
        class Rain :: AdverseConditions : "A level of rain that requires some use of wipers"
            values type = number range = (0,) units = "mm/h"
            class LightRain :: Rain : "Light rain requiring intermittent wipers"
                values subrange = (0,5]
            class ModerateRain :: Rain : "Rain requiring regular wipers"
                values subrange = (5,20)
            class HeavyRain :: Rain : "Rain requiring high-speed wipers"
                values subrange = [20,)

class SkyCondition : "The state of the sky: sun position, time of day"
    values type = number range = [0,8] units = "okta"
    attribute SunPosition as SunPosition
    attribute TimeOfDay as TimeOfDay
    class ClearSkies :: SkyCondition : "Completely clear sky"
        values subrange = [0,1]
    class PartlyCloudy :: SkyCondition : "Up to half of the sky is covered in clouds"
```

Environment part of the ontology.

Ability to tie to **real-world values**. Tooling to determine consistency.

Hierarchy. (of course)

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RoadDescription.ontology

```
five ai ontology specification RoadDescription


class Road : "The top level specification for the description of the carriageway"
    attribute SpeedLimit as SpeedLimit
    attribute CentralDividerMarking as CentralDividerMarking

class NormalRoad :: Road : "A normal road"
    optional attribute RoadEdge as NearSideRoadEdge default Curb
    optional attribute RoadsideFeature * as NearSideRoadsideFeature default Pavement
    optional attribute RoadsideMarking as NearSideRoadsideMarking
    attribute RoadScenery as RoadScenery
    attribute RoadGeometry as RoadGeometry
    attribute RoadSurface as RoadSurface default AsphaltSurface
    optional attribute RoadsideObstacle as NearSideRoadsideObstacle
    attribute Lane * as TrafficLanes
    optional attribute RoadEdge as FarSideRoadEdge default Curb
    optional attribute RoadsideFeature * as FarSideRoadsideFeature default Pavement
    attribute RoadsideMarking as FarSideRoadsideMarking
    optional attribute RoadsideObstacle as FarSideRoadsideObstacle


class RoadWithoutCentralReservation :: NormalRoad : "A road without a central reservation"
    class SingleTrackRoad :: RoadWithoutCentralReservation : "Road limited by definition to only including a single lane in one carriageway"
        class ResidentalSingleTrack :: SingleTrackRoad : "A residential road with no lane marking a[illegible] traffic in both directions"
        class SingleTrackRoadWithPassingPlaces :: SingleTrackRoad : "A country road that only has one lane but passing places"

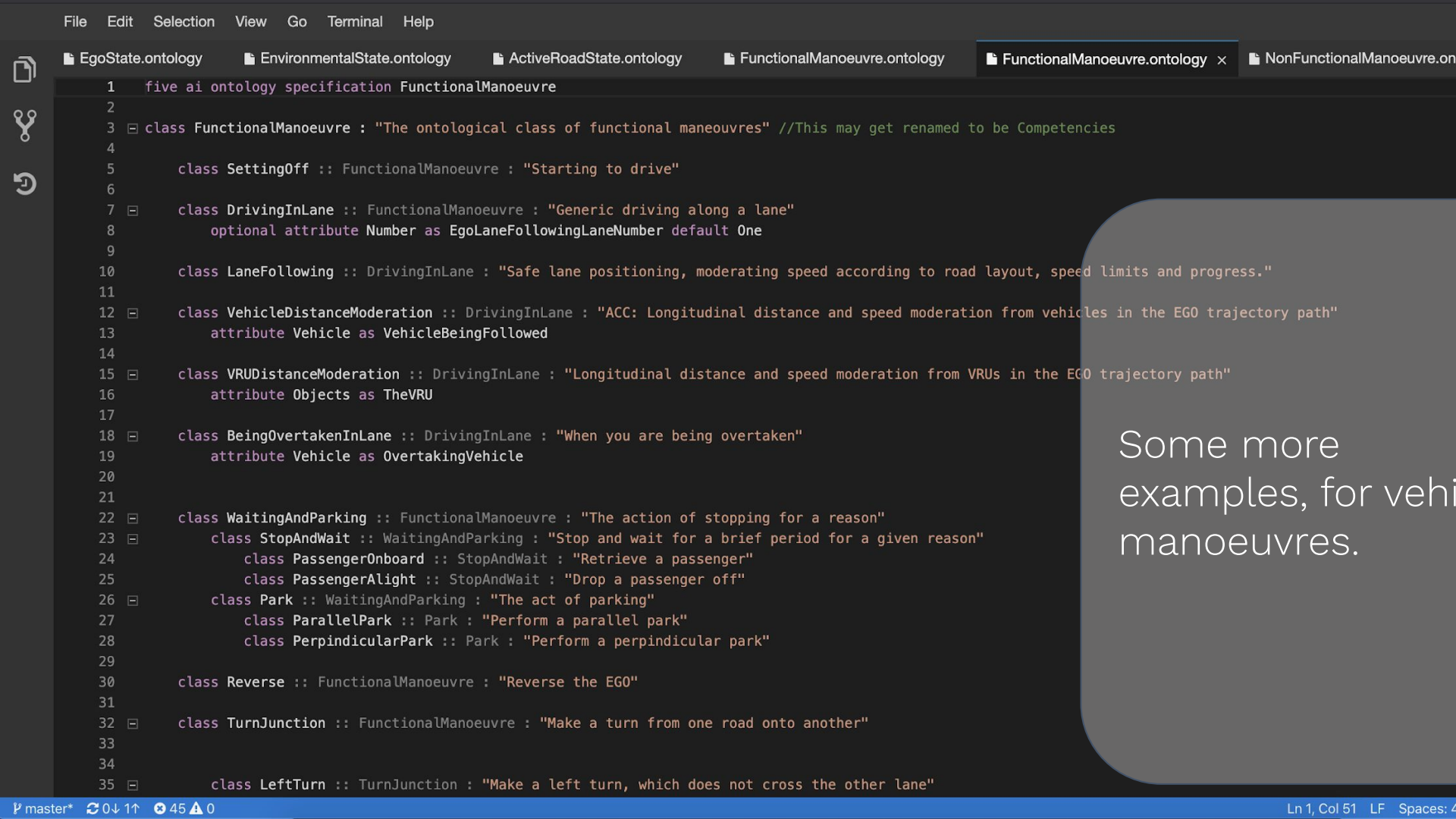
    class MultipleLaneRoad :: RoadWithoutCentralReservation : "A type of road that can have multiple lanes"
        class OneWayStreet :: MultipleLaneRoad: "A road layout with only one direction of travel"
        class SingleCarriageway :: MultipleLaneRoad : "A single carriageway road, without a well-defined center reservation"

class RoadWithCentralReservation :: NormalRoad : " A road with a central reservation"
    class DualCarriageway :: RoadWithCentralReservation : "A dual carriageway road, with a well-defined central reservation"
    class Motorway :: RoadWithCentralReservation : "A motorway class road"
```

Ditto for all the road elements that we see.

cf. Domain models in OpenX

Much more of this. Broadly similar to PAS 1883 but adds **Structure**


File Edit Selection View Go Terminal Help
EgoState.ontology
EnvironmentalState.ontology
ActiveRoadState.ontology
FunctionalManoeuvre.ontology
FunctionalManoeuvre.ontology
NonFunctionalManoeuvre.on
five ai ontology specification FunctionalManoeuvre
class FunctionalManoeuvre : "The ontological class of functional maneouvres" //This may get renamed to be Competencies
class SettingOff :: FunctionalManoeuvre : "Starting to drive"
class DrivingInLane :: FunctionalManoeuvre : "Generic driving along a lane"
optional attribute Number as EgoLaneFollowingLaneNumber default One
class LaneFollowing :: DrivingInLane : "Safe lane positioning, moderating speed according to road layout, speed limits and progress."
class VehicleDistanceModeration :: DrivingInLane : "ACC: Longitudinal distance and speed moderation from vehicles in the EGO trajectory path"
attribute Vehicle as VehicleBeingFollowed
class VRUDistanceModeration :: DrivingInLane : "Longitudinal distance and speed moderation from VRUs in the EGO trajectory path"
attribute Objects as TheVRU
class BeingOvertakenInLane :: DrivingInLane : "When you are being overtaken"
attribute Vehicle as OvertakingVehicle
class WaitingAndParking :: FunctionalManoeuvre : "The action of stopping for a reason"
class StopAndWait :: WaitingAndParking : "Stop and wait for a brief period for a given reason"
class PassengerOnboard :: StopAndWait : "Retrieve a passenger"
class PassengerAlight :: StopAndWait : "Drop a passenger off"
class Park :: WaitingAndParking : "The act of parking"
class ParallelPark :: Park : "Perform a parallel park"
class PerpindicularPark :: Park : "Perform a perpindicular park"
class Reverse :: FunctionalManoeuvre : "Reverse the EGO"
class TurnJunction :: FunctionalManoeuvre : "Make a turn from one road onto another"
class LeftTurn :: TurnJunction : "Make a left turn, which does not cross the other lane"
Some more examples, for vehi manoeuvres.
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London.odd | Objects.ontology ×

```
4    class Vehicle :: Objects : "Generic vehicle"
5        class Car :: Vehicle : "Generic car class"
6            class NormalCar :: Car : "Guidance: Category M1 or N1 vehicles as per (Vehicle Certification Agency, n.d.) and inclu
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```

ODD

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London.odd

```
five ai odd definition London

default is permissive
//Any ontology element not explicitly mentioned will be accepted as part of the ODD

global definitions
    for GenericTrafficDensity we allow  [LowTrafficDensity, MediumTrafficDensity]

    for ActiveRoadState attribute PertinentSceneElements we do not allow [LearnerOrNewDriverCar,
                                WideLoadLorry,
                                ArticulatedBus,
                                EmergencyVehicle,
                                Cyclist,
                                HorseRider,
                                NonRoadRespectingObjects]
    for AirParticulateMatter we allow [ClearAir]
    for WeatherCondition we allow [ClearCalm, LightRain]
    for TimeOfDay we allow [Daylight]
    for WindLevel we do not allow [StrongWinds]
    for GroundCondition we allow [DryGround, WetGround]
    for AlteredCondition we do not allow anything


    for FunctionalManoeuvre we allow [SettingOff,
                                LaneFollowing,
                                VehicleDistanceModeration,
                                StopAndWait,
                                LeftTurnMinorToMajor,
                                LeftTurnMajorToMinor,
                                RoundaboutExit,
                                EnterRoundabout,
                                OvertakeSingleCarriageway]

    for NonFunctionalManoeuvre we allow [DisplayIndicatorLights]
    for Road we allow [SingleCarriageway, OneWayStreet, DualCarriageway,CompactRoundabout]
```

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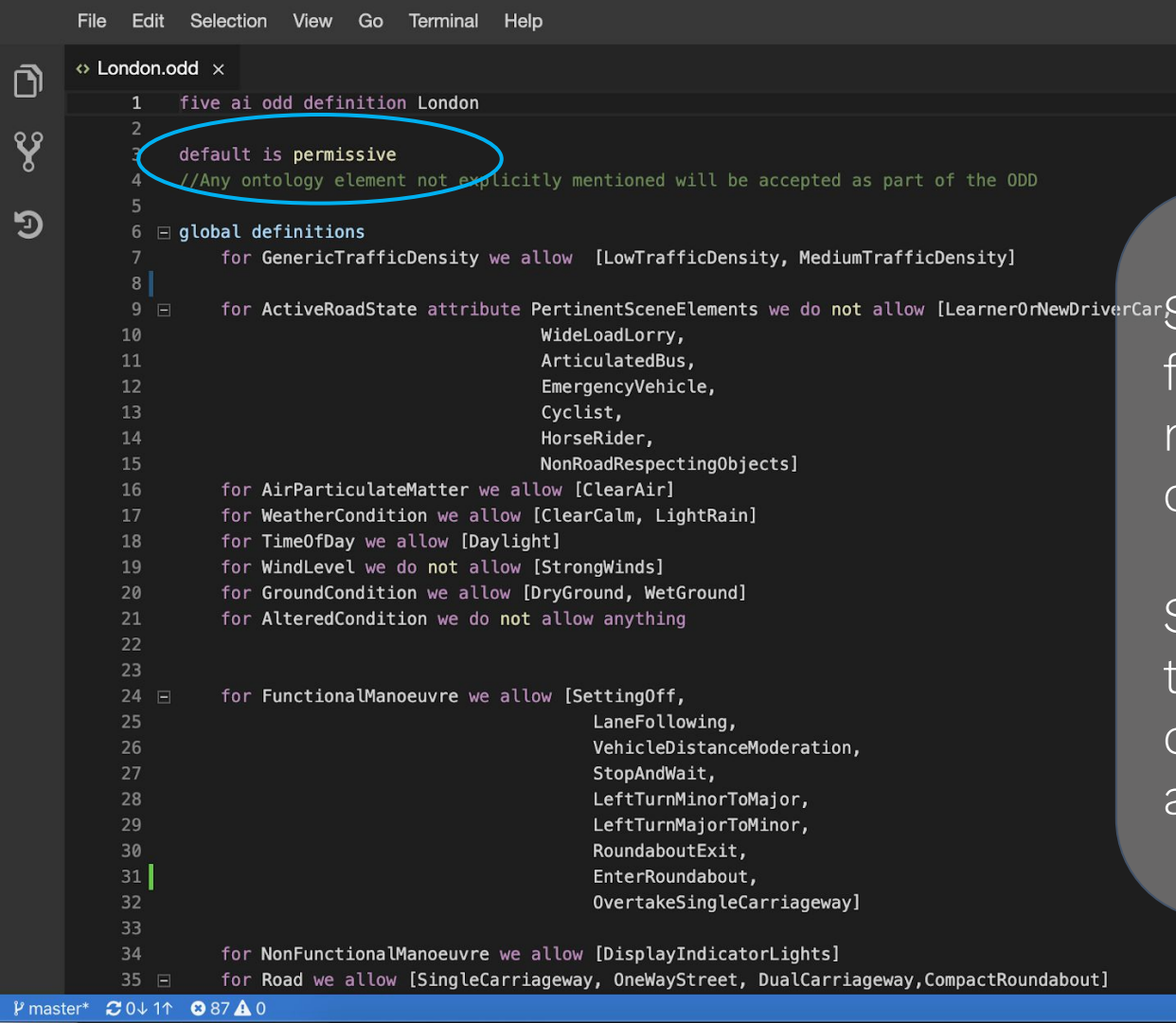
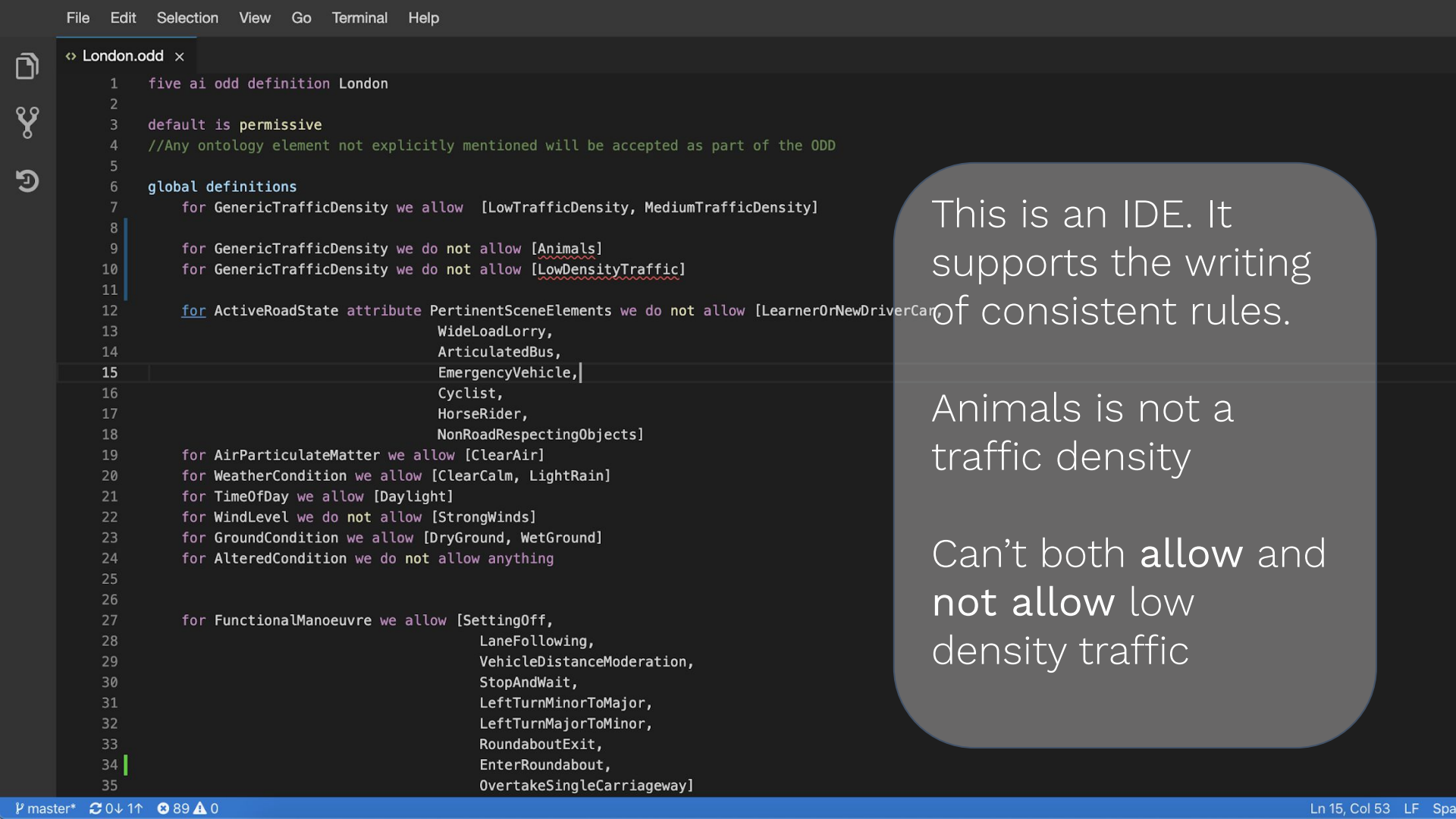
Domain Specific Language for declaring which parts of our ontology are in the ODD



Specific mechanism for parts of ontology not mentioned. Other option is restrictive

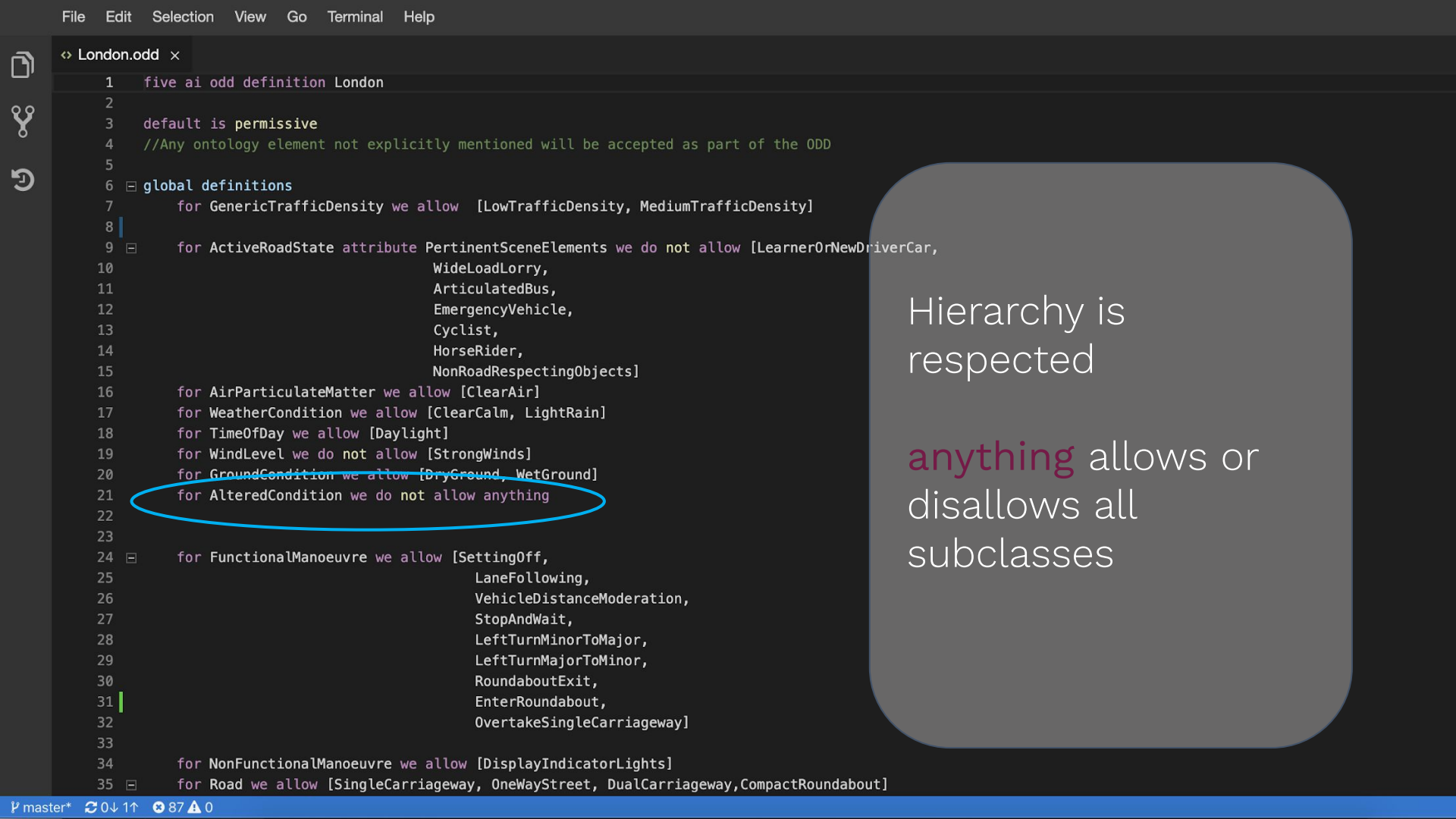
Simple syntax for talking about single dimensions and attributes



This is an IDE. It supports the writing of consistent rules.

Animals is not a traffic density

Can't both **allow** and **not allow** low density traffic


File Edit Selection View Go Terminal Help
London.odd
1 five ai odd definition London
3 default is permissive
4 //Any ontology element not explicitly mentioned will be accepted as part of the ODD
6 global definitions
7 for GenericTrafficDensity we allow [LowTrafficDensity, MediumTrafficDensity]
9 for ActiveRoadState attribute PertinentSceneElements we do not allow [LearnerOrNewDriverCar,
10 WideLoadLorry,
11 ArticulatedBus,
12 EmergencyVehicle,
13 Cyclist,
14 HorseRider,
15 NonRoadRespectingObjects]
16 for AirParticulateMatter we allow [ClearAir]
17 for WeatherCondition we allow [ClearCalm, LightRain]
18 for TimeOfDay we allow [Daylight]
19 for WindLevel we do not allow [StrongWinds]
20 for GroundCondition we allow [DryGround, WetGround]
21 for AlteredCondition we do not allow anything
24 for FunctionalManoeuvre we allow [SettingOff,
25 LaneFollowing,
26 VehicleDistanceModeration,
27 StopAndWait,
28 LeftTurnMinorToMajor,
29 LeftTurnMajorToMinor,
30 RoundaboutExit,
31 EnterRoundabout,
32 OvertakeSingleCarriageway]
34 for NonFunctionalManoeuvre we allow [DisplayIndicatorLights]
35 for Road we allow [SingleCarriageway, OneWayStreet, DualCarriageway,CompactRoundabout]
master* 0↓ 1↑ 87 0
Hierarchy is respected
anything allows or disallows all subclasses

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London.odd

```
41
42      for SceneEnvironmentState we do not allow [SchoolArea, HomeZone, QuietZone, SharedSpace]
43      for RoadIntersectionFeature we allow [CompactRoundabout,
44                                            TJunction,
45                                            Crossroads,
46                                            LaneSplit,
47                                            LaneMerge,
48                                            RoundaboutEntrance]
49
50      for PointRoadFeature we do not allow    [EquestrianCrossing,
51                                               TrafficCalming,
52                                               RoadWork,
53                                               LevelCrossing]
54
55
56  local restrictions
57
58      when Roundabout we do not allow [MediumTrafficDensity]
59      when Roundabout we do not allow [Pedestrian]
60      when TJunction we do not allow [MediumTrafficDensity]
61      when LightRain we do not allow [DualCarriageway,Roundabout]
62      when LightRain we do not allow [Fifty, Sixty] //Speeds we cannot drive
```

Finer grained control over your ODD specification via the ‘local restrictions’

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High-level scene annotation

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London.odd | ROB-060-Roundabout.scene | TestingDHC.dhc

```
five ai scene specification Example

using odd London
check dhc UKHighwayCode

//Scene 1: Entrance to the roundabout
static scene RoundaboutEntrance :
    - RoadLayout is SingleCarriageway with
        - CentralDividerMarking is SolidCentralDivider
        - NearSideRoadsideFeature is Pavement
        - NearSideRoadEdge is Cu
        - NearSideRoadsideMarkir
        - RoadGeometry is RoadGe
            - LateralRoadGeometr
            - VerticalRoadGeomet
        - RoadSurface is Asphalt
        - SpeedLimit is Thirty
        - FarSideRoadsideFeature
        - FarSideRoadEdge is Cur
        - FarSideRoadsideMarking
        - TrafficLanes are
            * Lane with
                - LaneNumber is
                - LaneType is No
                - LaneDirection
            * Lane with
                - LaneNumber is
                - LaneType is No
                - LaneDirection
    - SceneEnvironmentState is U
    - RoadFeature is RoundaboutE

dynamic scene ApproachRoundabout
    with static scene Roundabout
    environment :
```

High-level static scene description

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London.odd | ROB-060-Roundabout.scene ×

```
32
33  dynamic scene ApproachRoundabout :
34      with static scene RoundaboutEntrance
35      environment :
36          - SkyCondition is ClearSkies with
37              - SunPosition is SunFromSouth
38              - TimeOfDay is Twilight
39          - WeatherCondition is ClearCalm
40          - GroundCondition is DryGround
41      active road :
42          - GenericTrafficDensity is MediumTrafficDensity
43          - PertinentSceneElements are
44              * Car
45              * Lorry
46      ego state :
47          - EgoManoeuvre is EnterRoundabout with
48              - LaneNumber is One
49
50  dynamic scene EnterRoundabout :
51      with static scene RoundaboutEntrance
52      environment :
53          - SkyCondition is ClearSkies with
54              - SunPosition is SunFromSouth
55              - TimeOfDay is Daylight
56          - WeatherCondition is ClearCalm
57          - GroundCondition is DryGround
58      active road :
59          - GenericTrafficDensity is LowTrafficDensity
60          - PertinentSceneElements are
61              * Car
62      ego state :
63          - EgoManoeuvre is VehicleDistanceModeration with
```

master* 0↓ 1↑ 87 0 Ln 5, Col 1

High-level dynamic scene. Comes from OpenScenario + TraceFormat

ODD is checked in these languages

Writing road rules

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Example.dhc × TestingDHC.dhc TestOracle.dhc WorldScene.ontology

```
five ai dhc specification TestOracle

dhc rule DIR_01 : "No Collision: Ego shall not collide with any other vehicle"
    type = safety
    version 0.0.1
    when EgoManoeuvre = * //i.e. anything
    then zeroVehicleIntersection() // Safety Property Language

dhc rule DIR_02 : "Driving inside the road: Ego shall always drive fully inside the road"
    type = safety
    version 0.0.1
    when not AlteredCondition = EmergencyVehicleNearby
    then zeroEdgeOfRoadIntersection()

dhc rule LF_01 : "Speed Limit: Ego shall not exceed the 95% of the speed limit of the road that it is travelling on"
    type = safety
    version 0.0.2
    when RoadLayout = SingleCarriageway
    then speedLimitLessThanFactor(fraction="0.8")

dhc rule LF_01 : "Speed Limit: Ego shall not exceed the 95% of the speed limit of the road that it is travelling on"
    type = safety
    version 0.0.2
    when RoadLayout = DualCarriageway
    then speedLimitLessThanFactor(fraction="0.95")

dhc rule CR_01 : "Ego should not progress across the crossing if a pedestrian is on it"
    type = safety
    version 0.0.1
    when RoadFeature = PedestrianCrossing
    then noProgressIfPedestrianOnCrossing(pavementBuffer="0.1", crossingBuffer="0.1")

dhc rule CR_02 : "Ego should not come to a stop on a pedestrian crossing"
    type = safety
    version 0.0.1
```

Formal rule specification.

Combines Ontology as a predicate with queries on scenarios (observations in OSC 2.0)

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Use Cases

Use Cases

- As an engineer, I would like to understand exactly what “gentle acceleration”, “light rain”, “merge in turn” means in my company
- As a Verification engineer, I should have confidence that when I choose “light rain”, “dual carriageway” etc. in my scenario language, it will be the same as my system is supposed to consider it in the real world
- I would like to be able to formally specify my ODD
- I would like to check the consistency of my formal definitions

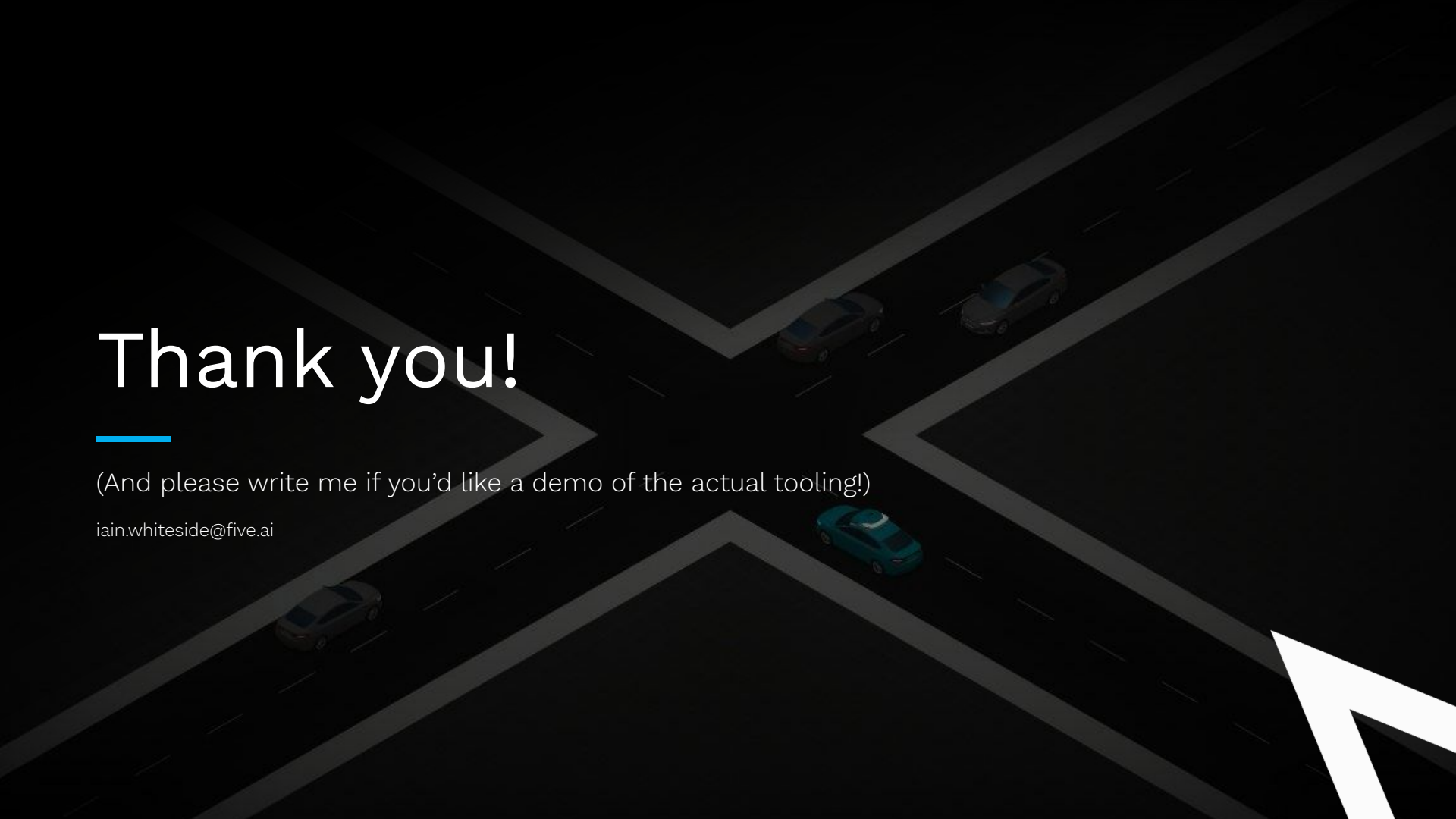
Use Cases

- As a validation engineer, I would like to be able to extend my ODD/Ontology (Specification) when I discover an edge case
- As a safety engineer, I would like to be able to **measure** how well I have scenarios covering my operating domain
- As a field operations engineer, I would like to be able to label directly using the ontology
- As an annotator, I would like to label in accordance with the ontology

Requirements

Requirements

- Formal
  - Need to be able to reason about it
  - Need to be able to ‘package’ and share
- OpenDrive and OpenScenario should map directly
  - domain model = ontology
- ODD is complex -- you need support to write it
  - Have languages
- Uniform between real and simulation
  - Otherwise, no safety guarantees from simulation?
  - Traceability to **safety case**



Thank you!

(And please write me if you'd like a demo of the actual tooling!)

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