Ontologies and ODDs at Five

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📌 Topics

- Five + Iain
- Importance of ODD/Operating Domain
- Our Approach
- A language for ODD specification
- ODD checking
- 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

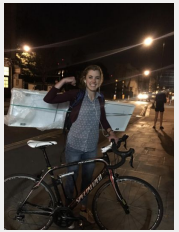
🙃The ODD Parac

well and good.

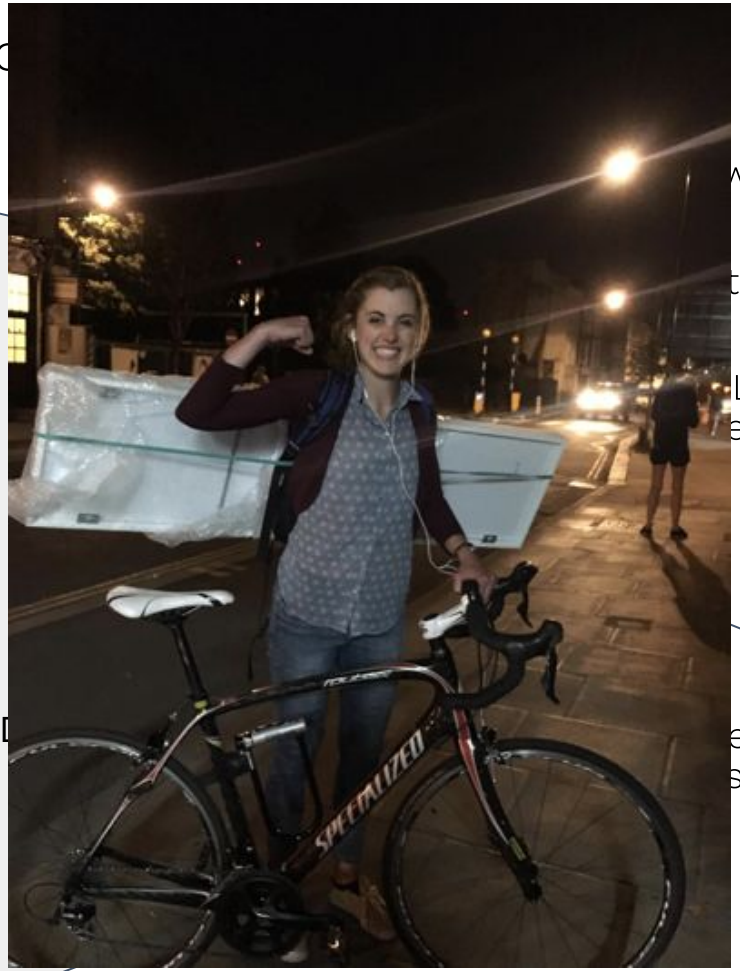
trials with safety drivers.

Level 4 services,
ever:

erating Domain" is at
st **as important**

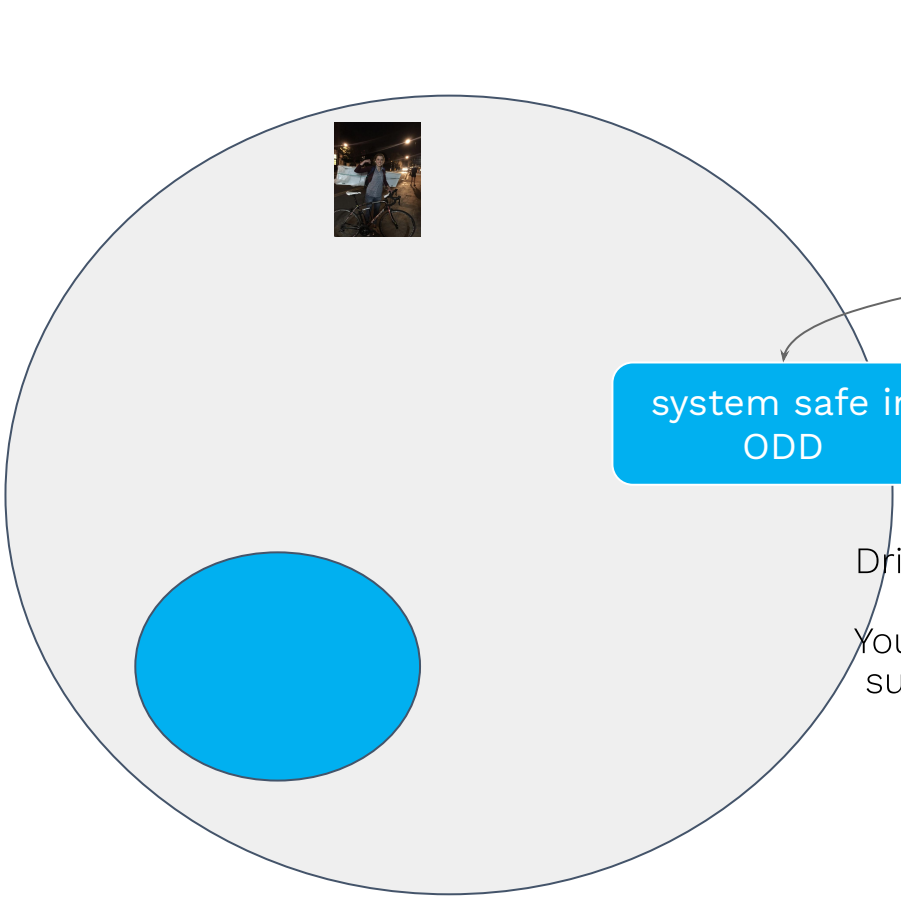


An ODD



*maybe not really a paradox, but it sounds catchy

🙃 The ODD Paradox*



system is safe

operational design domain

Digital road rules

system safe in ODD

system detects ODD

MRC safe

Driving ontology needs to cover your whole operating domain.
Your ODD classification needs to select the subset where you consider safe operation

A sophisticated system needs to understand the whole domain

This might be even more complex!

Our approach

5️⃣ Our approach

Build formal ontology for driving domain

An ODD is a subset of the cross-product of this complex ontology

Develop a specific format for specifying this subset formally

Tooling to support **development** and **detection** (sim + real)

Feed directly into into safety case: backbone for structure

Ontology

(domain model, if you will)

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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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2
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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 + **Structure**

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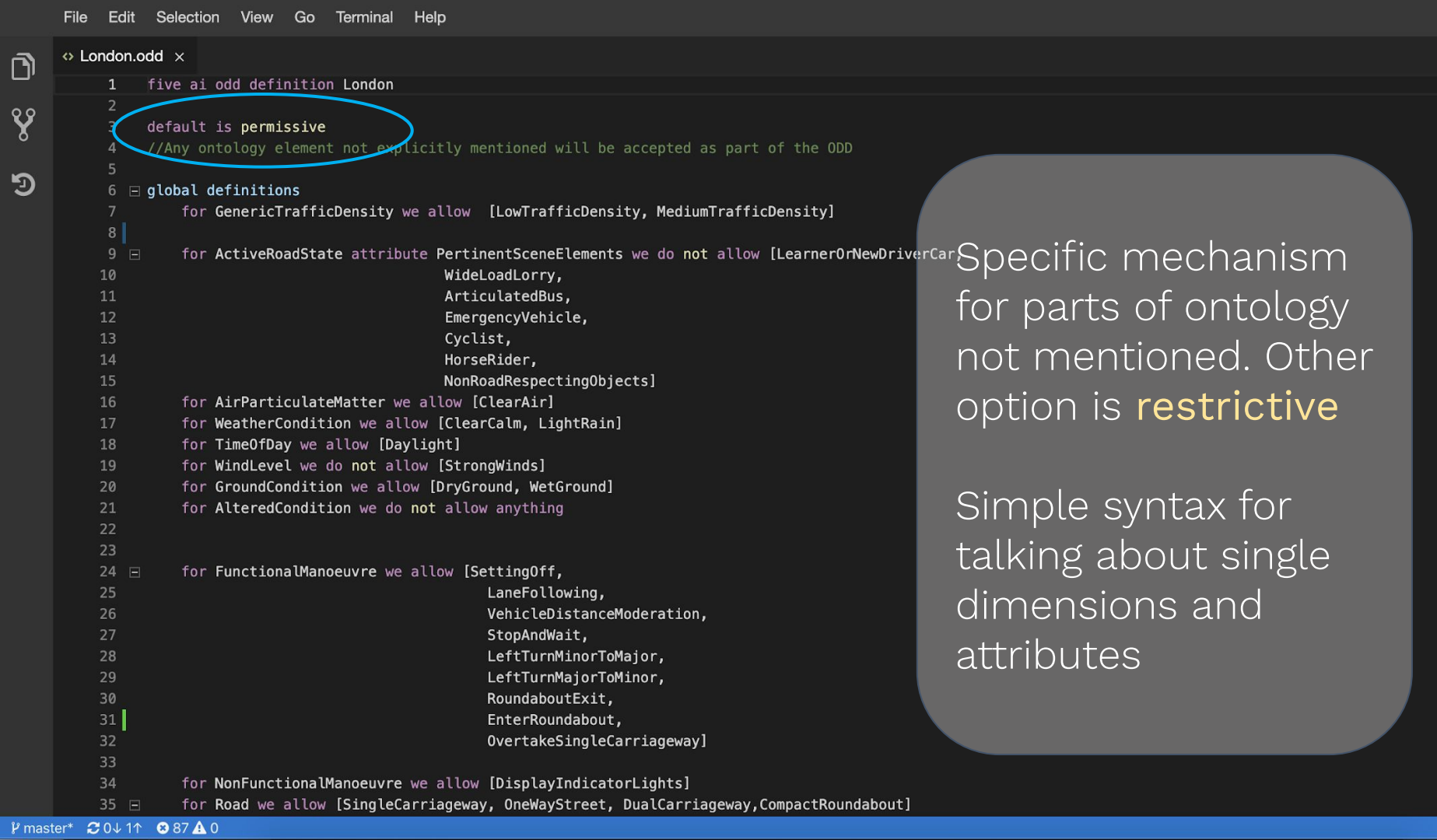
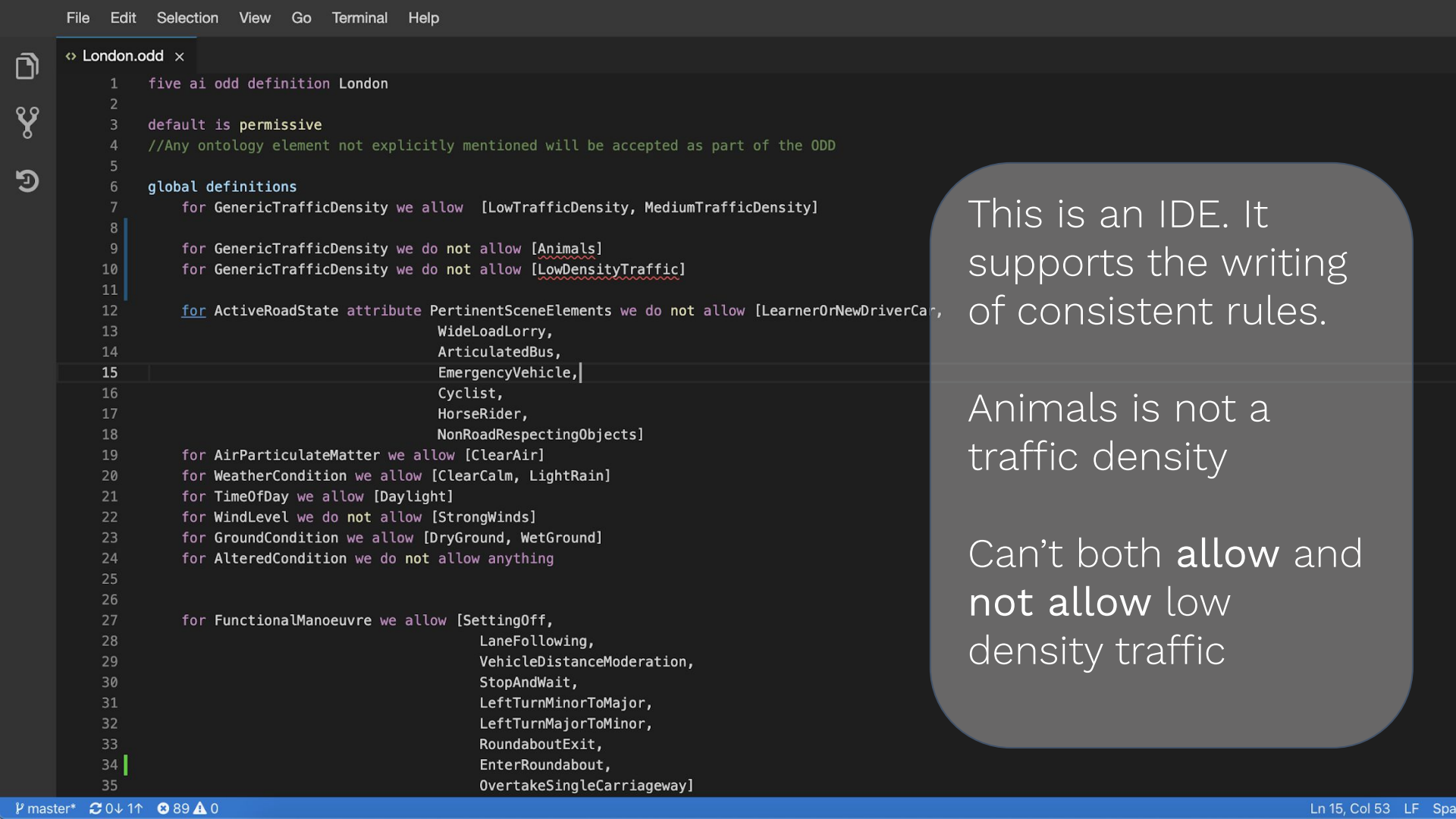
Domain Specific Language for declaring which parts of our ontology are in the ODD



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

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London.odd

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five ai odd definition London

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//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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Hierarchy is respected

anything allows or disallows all subclasses

EmergencyVehicle is not a leaf class

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London.odd × ROB-060-Roundabout.scene

```
37
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41      for Road we allow [SingleCarriageway, OneWayStreet, DualCarriageway,CompactRoundabout]
42          for Road attribute RoadSurface we allow [AsphaltSurface,ConcreteSurface]
43          for DualCarriageway attribute RoadSurface we allow [AsphaltSurface]
44          for Road attribute SpeedLimit we do not allow [Ten, Seventy]
45          for Road attribute CentralDividerMarking we allow anything
46          for Road attribute RoadScenery we allow [GreenAvenueCanyonScenery, GreenOpenScenery,
47                                                   SyntheticAvenueCanyonScenery, SyntheticOpenScenery]
48
49
50
51      for SceneEnvironmentState we do not allow [SchoolArea, HomeZone, QuietZone, SharedSpace]
52      for RoadIntersectionFeature we allow [CompactRoundabout,
53                                            TJunction,
54                                            Crossroads,
55                                            LaneSplit,
56                                            LaneMerge,
57                                            RoundaboutEntrance]
58
59      for PointRoadFeature we do not allow    [EquestrianCrossing,
60                                               TrafficCalming,
61                                               RoadWork,
62                                               LevelCrossing]
63
64
65  local restrictions
66
67      when Roundabout we do not allow [MediumTrafficDensity]
68      when Roundabout we do not allow [Pedestrian]
69      when TJunction we do not allow [MediumTrafficDensity]
70      when LightRain we do not allow [DualCarriageway,Roundabout]
71      when LightRain we do not allow [Fifty, Sixty] //Speeds we cannot drive
```

Sophisticated semantics for attributes w.r.t. hierarchy. For example, all road types other than DualCarriageway can have concrete surface.

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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
7           class LearnerOrNewDriverCar :: Car : "M1 or N1 car with learner or new driver plates"
8           class BlackCab :: Car : "A hackney carriage"
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```

File Edit Selection View Go Terminal Help

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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Usage Example

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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 Curb
        - NearSideRoadsideMarking is DoubleYellowLine
        - RoadGeometry is RoadGeometry with
            - LateralRoadGeometry is GentleBend
            - VerticalRoadGeometry is FlatRoad
        - RoadSurface is AsphaltSurface
        - SpeedLimit is Thirty
        - FarSideRoadsideFeature is Pavement
        - FarSideRoadEdge is Curb
        - FarSideRoadsideMarking is SingleYellowLine
        - TrafficLanes are
            * Lane with
                - LaneNumber is One
                - LaneType is NormalLaneOfTraffic
                - LaneDirection is EgoDirection
            * Lane with
                - LaneNumber is Two
                - LaneType is NormalLaneOfTraffic
                - LaneDirection is OncomingDirection
    - SceneEnvironmentState is UrbanEnvironment
    - RoadFeature is RoundaboutEntrance

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

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High-level static scene description

File Edit Selection View Go Terminal Help

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
```

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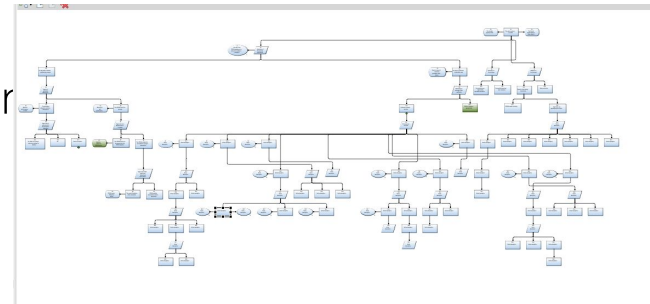
High-level dynamic scene

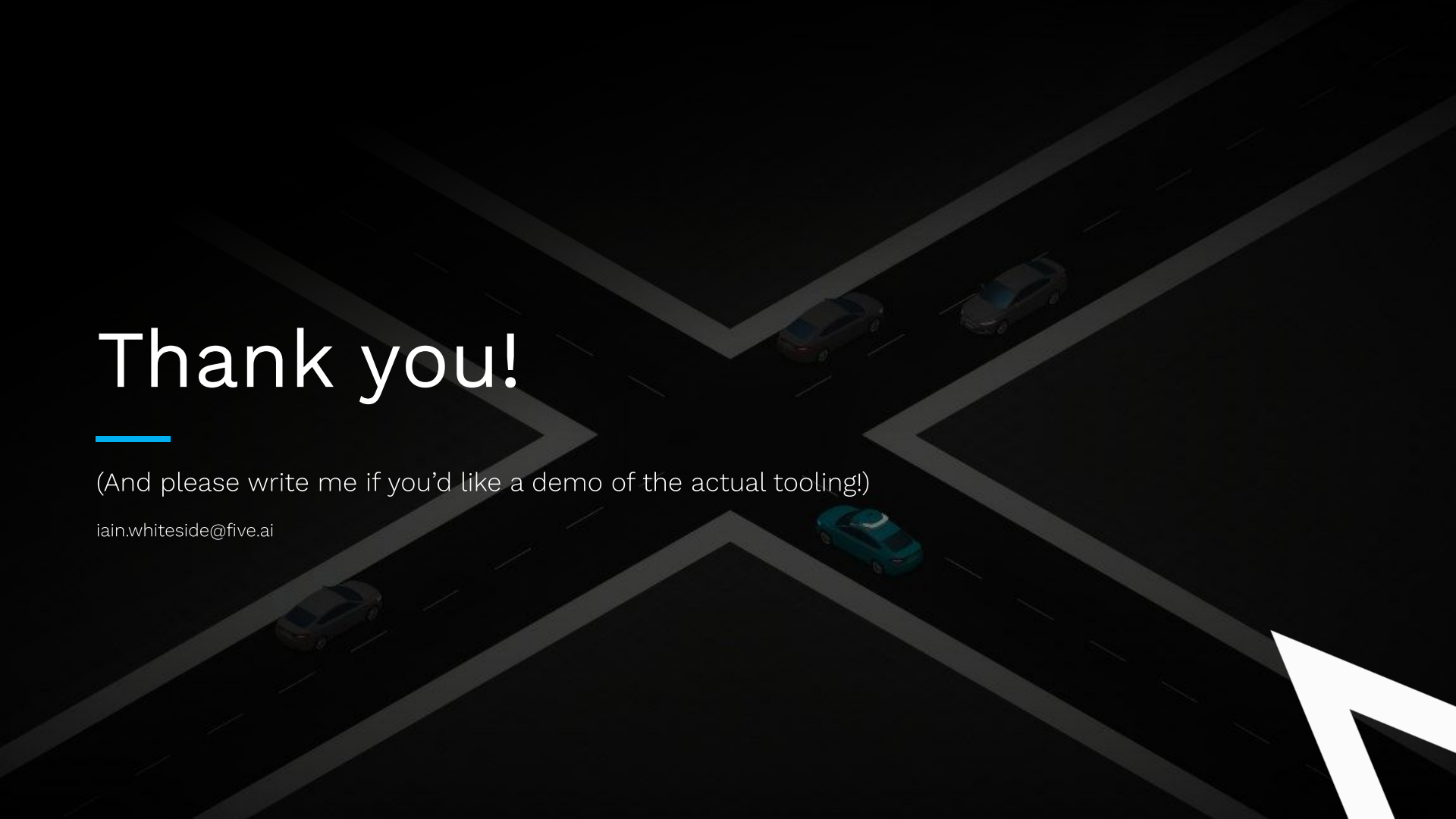
ODD is checked in these languages

Requirements

Requirements

- An ODD is subtle and nuanced
  - A table will **not** cut it
  - the power is in the attribute and local definitions
- OpenDrive and OpenScenario should map directly
  - via domain model = ontology
- ODD is complex -- you need support to write it
- Uniform between real and simulation
  - Otherwise, what's the point of simulation
  - Traceability to **safety case**





Thank you!

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

iain.whiteside@five.ai