

# Priyanka x20192037 Project CA

## Modelling, Simulation and Optimisation (H9MSO)

### The “Future Cities” Project in Trinity College Dublin investigates a “Self-Organising Motorway” in SimPy v.4

## Requirements¶

Your task is to investigate for suitable points along the motorway segment

the traffic density  $k$  (the number of vehicles per km across all available lanes), and the mean speed of the vehicles  $u$ , and for the overall motorway segment the traffic volume  $q$  (i.e. the total number of vehicles passing per hour across all available lanes), and the average total travelling time. depending on certain input parameter: motorway speed limits settings (60km/h, 80km/h, 100km/h, and 120km/h), inter-arrival time distributions (directly influencing the traffic density), and traffic mix (percentage of heavy goods vehicles, electrical, autonomous cars) Report the highest traffic volume the motorway segment can accommodate and articulate your recommendations regarding the setting of speed limits on the motorway segment.

## Importing all required libraries

```
In [1]: #Importing all required libraries
import pandas as pd
import numpy as np
import math
import random
import statistics
import matplotlib as mpl
import matplotlib.pyplot as plt
import scipy as sp
import scipy.stats as stats
import statsmodels.api as sm
import seaborn as sns
import simpy
import simpy.events as evt
import random
from random import random
```

```
In [2]: # Utilities  
def isZero(x,  $\epsilon$  = 0.00001):  
    return abs(x) <  $\epsilon$ 
```

## Bell Curve Random Generator

```

In [3]: gen_x_tab = None
        gen_y_tab = None

def pdfv(x, mean=0, sd=None, delta=None):

    if sd is None and delta is None:
        sd = 1
    elif sd is None and delta is not None:
        sd = delta/math.sqrt(6)*0.9275

    τ = math.sqrt(6)
    x = (x-mean)/sd*0.9275
    return np.where(abs(x)<τ, 5/(8*τ*sd)*(1-x**2/2+x**4/24+1/2)*0.9275, 0)

def rv(mean=0, sd=None, delta=None, alternating=None, rounding=None):

    if sd is None and delta is None:
        sd = 1
    elif sd is None and delta is not None:
        sd = delta/math.sqrt(6)*0.9275

    global gen_count, gen_x_tab, gen_y_tab

    if gen_x_tab is None:

        # initialise global variables
        gen_x_tab = list(np.linspace(-math.sqrt(6), -1.51, 500)) + \
                     list(np.linspace(-1.5, 0, 151))

        τ = math.sqrt(6)

        def cdf(x):
            return 5/(8*τ)*(x**5/120-x**3/6+x*3/2)+5/(8*τ)*(τ**5/120-τ**3/6+τ*
3/2)

        gen_y_tab = [ cdf(x) for x in gen_x_tab ]

    y, sign = random.random(), 1
    if y>0.5:
        y, sign = 1-y, -1
    if alternating is not None:
        sign = 1 if alternating%2==0 else -1

    for i in range(1, len(gen_x_tab)):
        if y < gen_y_tab[i]:
            x0 = gen_x_tab[i]
            y0 = gen_y_tab[i]
            x1 = gen_x_tab[i-1]
            y1 = gen_y_tab[i-1]
            x = mean+sign*((x0+(y-y0)*(x1-x0)/(y1-y0))*sd/0.9275)
            if type(rounding) is int and rounding>0:
                return round(x, rounding)
            else:
                return x

```

# Entities

```
In [4]: def normaliseDirection(d):  
        d = d.lower()  
        if d=='r' or d=='fast':  
            return 'fast'  
        elif d=='l' or d=='slow':  
            return 'slow'  
        else:  
            return None
```

## Lanes Entity

In [5]: LANE\_ID = 0

```
class Lane:

    def __init__(self, rec, length, speedLimit=None, merge=None):

        global LANE_ID
        self.id = LANE_ID
        LANE_ID += 1

        self.rec = rec
        self.x0 = 0
        self.length = length

        # speed limit on this lane segment in km/h
        self.speedLimit = speedLimit

        # indicates that at the end of the lane traffic has to merge to the left or right
        self.merge = merge

        self.vehicles = []

        self.next = None
        self.prev = None

        # lane attached to the left/right
        self.left = None
        self.right = None

        rec.recordLane(self)

    # defines generic str() method for Lanes
    def __str__(self):
        l = " L:--" if self.left is None else f" L:{self.left.id:0>2d}"
        r = " R:--" if self.right is None else f" R:{self.right.id:0>2d}"
        s = "" if self.speedLimit is None else f" speedLimit:{self.speedLimit:
d}km/h"
        return f"[{self.id:0>2d} x={self.x0:3.1f}m l={self.length:3.1f}m"+l+r+s+"]" + \
            ("\\ " if self.merge=='R' else "") + \
            ("/ " if self.merge=='L' else "") + \
            ("-" + str(self.next) if self.next is not None else "")

    def getLane(self, direction):
        if direction=='slow':
            return self.left
        elif direction=='fast':
            return self.right
        else:
            return None

    ## additional code
    # adding parallel lane on right side
    def attachRight(self, lane):
        self.right = lane
```

```

        lane.left = self
        lane.x0 = self.x0
        lane.speedLimit = self.speedLimit

## additional code
# adding parallel lane on right side
def attachLeft(self, lane):
    self.left = lane
    lane.right = self
    lane.x0 = self.x0
    lane.speedLimit = self.speedLimit

## additional code
# constructs a number of lane segments of the same length
# and attaches them to the right
def widenRight(self):
    lane = self
    newLane = Lane(self.rec, lane.length)
    lane.attachRight(newLane)
    while lane.next is not None:
        lane = lane.next
        newLane = Lane(self.rec, lane.length)
        lane.attachRight(newLane)
        newLane.prev = lane.prev.right
        newLane.prev.next = newLane
    return self.right

## additional code
# constructs a number of lane segments of the same length
# and attaches them to the right
def widenLeft(self):
    lane = self
    newLane = Lane(self.rec, lane.length)
    lane.attachLeft(newLane)
    while lane.next is not None:
        lane = lane.next
        newLane = Lane(self.rec, lane.length)
        lane.attachLeft(newLane)
        newLane.prev = lane.prev.left
        newLane.prev.next = newLane
    return self.left

# defines concatenation of lanes
def extend(self, lane):
    l = self
    while l.next is not None:
        l = l.next
    l.next = lane
    lane.x0 = l.x0+l.length
    lane.prev = l
    return self

def totalLength(self):
    total = self.length
    l = self
    while l.next is not None:
        l = l.next

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        total += l.length
    return total

def between(self, posBack, posFront):
    # make sure that the position of all cars is accurate
    # at this point in time
    for v in self.vehicles:
        v.updateOnly()
        # normally the list should be sorted, but just in case
    self.vehicles.sort(key=lambda v: v.pos)
    res = []
    for v in self.vehicles:
        if posBack < v.pos and v.pos-v.length < posFront:
            res.append(v)
    # if the required distance reaches over the end of the lane segment
    if posFront > self.length and self.next is not None:
        return res + self.next.between(0, posFront-self.length)
    elif posBack < 0 and self.prev is not None:
        return self.prev.between(self.prev.length+posBack, self.prev.length
h) + res
    else:
        return res

def inFront(self, pos, far):
    # make sure that the position of all cars is accurate
    # at this point in time
    for v in self.vehicles:
        v.updateOnly()
    # normally the list should be sorted, but just in case
    self.vehicles.sort(key=lambda v: v.pos)
    for v in self.vehicles:
        if v.pos > pos:
            return v if v.pos-pos<far else None
    # there is none in front in this lane
    # if the free lane in front is long enough or there is no next lane
    if self.length-pos>far or self.next is None:
        return None
    else:
        return self.next.inFront(0, far-(self.length-pos))

def behind(self, pos, far):
    # make sure that the position of all cars is accurate
    # at this point in time
    for v in self.vehicles:
        v.updateOnly()
    # This time we sort in reverse order
    self.vehicles.sort(key=lambda v: v.pos, reverse=True)
    for v in self.vehicles:
        if v.pos < pos:
            return v if pos-v.pos<far else None
    # there is none behind in this lane
    # if the free lane in behind is long enough or there is no previous La
ne
    if pos>far or self.prev is None:
        return None
    else:
        return self.prev.behind(self.prev.length, far-pos)

```

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def enter(self, vehicle, pos=0, laneChange=False):
    self.vehicles.insert(0, vehicle)
    vehicle.pos = pos
    vehicle.lane = self
    vehicle.rec.record(vehicle, event="enter lane" + (f" {self.id:d}" if laneChange else ""))

def leave(self, vehicle, laneChange=False):
    vehicle.rec.record(vehicle, event="leave lane" + (f" {self.id:d}" if laneChange else ""))
    vehicle.lane = None
    self.vehicles.remove(vehicle)

```

## Vehicle Entity

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In [6]: def isRunning(p):
        return p is not None and p.running

def isCrashed(p):
    return p is not None and p.crashed

```



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In [7]: VEHICLE_ID = 0
#vehicle_dict=dict of carname: (max_speed,max_acceleration,length and ideally
width)

#VEHICLE_DICT={"Nissan Saloon":(240,4.67,5.12),"Renault Clio Hatchback":(161,
1.6,4.05),"Ford Fiesta Hatchback":(200,2.9,4.068),"Electric car":(160,2.3,3.8
9),"HGV":(140,1.8,15)}

class Vehicle:
    def __init__(self, rec,
        startingLane=None, startingPos=0,
        t0=0, x0=0, dx0=0, ddx0=0, dddx0=0,
        vmax=None, vmax_var=None,a_max=None,
        t=[], v=[],VEHICLE_MODEL="car"):

        global VEHICLE_ID
        self.id = VEHICLE_ID
        VEHICLE_ID += 1
        #self.vehicle=List(VEHICLE_DICT.keys())[VEHICLE_ID-1]

        self.VEHICLE_MODEL=VEHICLE_MODEL

        if self.VEHICLE_MODEL=="car":
            self.a_max=2.5
            self.a_brake = -4.0 # [m/s2]
            self.a_coast = -0.6 # [m/s2]
            self.length = 4

        elif self.VEHICLE_MODEL=="HGV":
            self.a_max=1.8
            self.a_brake = -2.5 # [m/s2]
            self.a_coast = -1.3 # [m/s2]
            self.length = 15

        elif self.VEHICLE_MODEL=="electric car":

            self.a_max= 4.6
            self.a_brake = -8.0 # [m/s2]
            self.a_coast = -1.8 # [m/s2]
            self.length = 4.6

        else:
            self.a_brake = -4.0 # [m/s2]    Tesla: -8.0 # [m/s2]
            self.a_coast = -0.6 # [m/s2]    Tesla: -1.8 # [m/s2]
            self.a_max= 2.5
            self.length = 4.6

        self.a_max = a_max # [m/s2]    Tesla: 4.6 # [m/s2]
            # Note: 2.5m/s2 corresponds to 0-100km/h om 11s
        # self.length = 4 # [m] Length of the vehicle
        self.VEHICLE_LENGTH=4

        self.absolute_speed_time_tolerance = 2 # [s]

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self.relative_speed_time_tolerance = 5 # [s]
self.far_away_in_front = 200 # [m]
self.far_away_in_back = 80 # [m]
self.min_action_time = 0.5 # [s]

self.lane_change_time = 3 # [s]
self.min_speed_diff = 2 # [m/s]

## if not None the preferred max free velocity
self.vmax = vmax
self.vmax_variation = vmax_var if vmax_var is not None else 0.05
self.timing = 100 # [s]
self.timing_variation = 0.30

self.env = rec.env
self.rec = rec

self.startingLane = startingLane
self.startingPos = startingPos
self.lane = None
self.pos = 0

# speedLimit once recognised
self.speedLimit = None

## second lane reference during changing of lanes
self.oldLane = None

self.alternator = 0

self.t0 = t0
self.x0 = x0    # [m] the reference point is on the front of the vehicle
                # the body of the vehicle of the given length is behind

self.dx0 = dx0
self.ddx0 = ddx0
self.dddx0 = dddx0

self.t_target = t
self.v_target = v
# while there is an adjustment of velocity in progress
# the current_target is set
self.current_target = None

# trace flags
self.traceAdjustVelocity = False
self.traceInterrupt = False
self.traceBraking = False
self.traceCrash = False
self.traceSurround = False
self.traceOvertaking = False

# start process
self.running = False
self.crashed = False

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# Flags used for temporarily exclusive behaviour
self.laneChangeControl = False
    # This flag is used to block automatic overtaking
    # while processing explicit lane change control
self.braking = False
    # This flag is used to prevent interrupting braking for braking

self.changingLane = False
    # This flag is used to prevent interrupting lanechanging

self.processRef = None
self.env.process(self.process())

def trace(self, message):
    print(f"t={self.t0:7,.1f}s x={self.x0:7,.1f}m v{self.id:d}", message)

def isNotFasterThan(self, other):
    return True if other is None else self.dx0 <= other.dx0

def isNotSlowerThan(self, other):
    return True if other is None else other.dx0 <= self.dx0

## adapted to handle lane information
def updateOnly(self):
    t = self.env.now
    if t < self.t0 or not self.running:
        return False
    if t > self.t0:
        dt = t - self.t0
        ddx = self.ddx0 + self.dddx0*dt
        dx = self.dx0 + self.ddx0*dt + self.dddx0*dt*dt/2
        Δx = self.dx0*dt + self.ddx0*dt*dt/2 + self.dddx0*dt*dt*dt/6
        x = round(self.x0 + Δx, 2)
        self.t0, self.x0, self.dx0, self.ddx0 = t, x, dx, ddx

    ## begin additional code
    self.pos = round(self.pos+Δx, 2)
    # update lane information if necessary
    if self.pos >= self.lane.length:
        nextPos = self.pos - self.lane.length
        nextLane = self.lane.next
        self.lane.leave(self)
        if nextLane is None:
            self.oldLane = None
            self.rec.record(self, event='end')
            self.running = False
            return False
        else:
            nextLane.enter(self, pos=nextPos)
    ## end additional code

    return True

## minor change only
def update(self):

    self.surround = Surround(self)

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## instead of direct link, call method
inFront = self.surround.front

# if there is a running or crashed vehicle in front and
# we have crashed into the rear end of that vehicle
if inFront is not None and inFront.x0-inFront.length < self.x0+self.VEHIC
HICLE_LENGTH:
    self.crash(inFront)

# if the speedLimit changes...
elif self.speedLimit != self.lane.speedLimit:
    self.speedLimit = self.lane.speedLimit
    if self.speedLimit is None:
        # end of speed limit, return to default behaviour
        if self.vmax is not None and self.vmax>self.dx0:
             $\Delta t = \max(\text{self.min\_action\_time}, (\text{self.vmax}-\text{self.dx0})/\text{self.a\_max})$ 
            self.setTarget( $\Delta t$ , self.vmax)
        else:
            vmax = self.speedLimit/3.6
            vmax = rv(mean=vmax, delta=self.vmax_variation*vmax)
            if vmax<self.dx0:
                # when the new speedLimit is lower than current speed, coast down
                 $\Delta t = \max(\text{self.min\_action\_time}, (\text{self.dx0}-\text{vmax})/\text{self.a\_coast})$ 
                self.setTarget( $\Delta t$ , vmax)
            else:
                # when the new speedLimit is higher than current speed, accelerate at half max a_max
                 $\Delta t = \max(\text{self.min\_action\_time}, 2*(\text{vmax}-\text{self.dx0})/\text{self.a\_max})$ 
                self.setTarget( $\Delta t$ , vmax)

# if at the end of the lane merging is required
elif self.lane.merge is not None and \
    not self.braking and not self.laneChangeControl and not self.changingLane:
    if self.lane.merge == 'R':
        if self.surround.rightLane is not None and \
            self.surround.right is None and \
            self.isNotFasterThan(self.surround.rightFront) and \
            self.isNotSlowerThan(self.surround.rightBack):
            self.setTarget(self.lane_change_time, 'fast')
    elif self.lane.merge == 'L':
        if self.surround.leftLane is not None and \
            self.surround.left is None and \
            self.isNotFasterThan(self.surround.leftFront) and \
            self.isNotSlowerThan(self.surround.leftBack):
            self.setTarget(self.lane_change_time, 'slow')

# start overtaking maneuver by changing into fast lane
elif inFront is not None and \
    not self.braking and not self.laneChangeControl and not self.changingLane and \
    self.dx0 > inFront.dx0 + self.min_speed_diff and \

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        self.x0 + (self.lane_change_time+self.absolute_speed_time_tole
range)*self.dx0 > inFront.x0-inFront.length and \
        self.surround.rightLane is not None and \
        self.surround.right is None and \
        self.isNotFasterThan(self.surround.rightFront) and \
        self.isNotSlowerThan(self.surround.rightBack):
            self.setTarget(self.lane_change_time, 'fast')

# if there is a vehicle in front
# which drives slower and
# the distance to that vehicle in front is at current speed
# less than the critical time tolerance of this driver
        elif inFront is not None and \
            not self.braking and not self.laneChangeControl and not self.c
hangingLane and \
            self.dx0 > inFront.dx0 and \
            self.x0 + self.absolute_speed_time_tolerance*self.dx0 > inFron
t.x0:
            # note that self.a_coast is a negative acceleration
            Δt = max(self.min_action_time, (inFront.dx0-self.dx0)/self.a_coast
)

            if self.current_target is None or \
                not isZero(self.current_target-inFront.dx0):
                self.setTarget(Δt, inFront.dx0)

        # end overtaking by returning to slow lane
        elif self.surround.leftLane is not None and \
            not self.braking and not self.laneChangeControl and not self.c
hangingLane and \
            self.surround.leftLane.totalLength()-self.pos>100 and \
            self.surround.left is None and \
            self.isNotSlowerThan(self.surround.leftBack) and \
            self.surround.leftFront is None:
            self.setTarget(self.lane_change_time, 'slow')

## code remains unchanged
def setTarget(self, t, v):
    self.t_target = [ t ] + self.t_target
    self.v_target = [ v ] + self.v_target
    self.interruptProcess()

## minor change only
def process(self):

    # delay start to the given time t-
    if self.t0>self.env.now:
        yield self.env.timeout(self.t0-self.env.now)
    self.t0 = self.env.now
    self.running = True
    self.rec.startRecording(self)

    ## begin additional code
    ## enter the first lane
    self.startingLane.enter(self)
    ## end additional code

    while self.updateOnly():

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    ## instead of direct link, call method
    inFront = self.lane.inFront(self.pos, self.far_away_in_front) \
        if self.lane is not None else None

    # if the car in front is slower and we are a bit too near on its h
eals...
    if inFront is not None and inFront.dx0 < self.dx0 and \
        inFront.x0-inFront.length < \
            self.x0 + self.relative_speed_time_tolerance*(self.dx0
-inFront.dx0):
        yield from self.emergencyBraking(inFront.dx0)
        if not isZero(self.dx0-inFront.dx0):
            # after emergency breaking adjust to the speed of the car
in front...
            Δt = 1
            self.setTarget(Δt, inFront.dx0)
            continue

    if len(self.t_target)>0:

        t_target = self.t_target[0]
        v_target = self.v_target[0]
        self.t_target = self.t_target[1:]
        self.v_target = self.v_target[1:]

        if type(v_target) is str:

            # explicit overtake commands temporarily
            # disable overtaking
            if v_target=='R':
                self.laneChangeControl = True
            elif v_target=='L':
                self.laneChangeControl = False

            direction = normaliseDirection(v_target)
            if self.lane.getLane(direction) is not None:
                yield from self.changeLane(inFront, direction, t_targe
t)

        ## the rest is what was there before
        else:
            v0 = self.dx0
            v1 = v_target
            Δt = t_target
            if isZero(v1-v0):
                yield from self.continueAtSameSpeed(Δt)
            else:
                yield from self.adjustVelocity(v1-v0, Δt)

    ## additional code
    elif self.vmax is not None:

        # if the explicit control strategy is exhausted and
        # a target maximum speed is set the vehicle will follow
        # a random speed around the target maximum speed

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        ## additional code
        vmax = self.vmax
        if self.speedLimit is not None:
            vmax = self.speedLimit/3.6
            vmax = rv(mean=vmax, delta=self.vmax_variation*vmax)

        # as long there is no vehicle in front or the vehicle in front
        # is far enough ahead
        if inFront is None or \
            self.x0 + self.relative_speed_time_tolerance*(self.dx0-inFront.dx0) < inFront.x0:
            v0 = self.dx0
            self.alternator += 1
            v1 = rv(mean=vmax,
                    delta=self.vmax_variation*vmax,
                    alternating=self.alternator,
                    rounding=2)
            Δt = rv(mean=self.timing,
                    delta=self.timing*self.timing_variation,
                    rounding=1)

            yield from self.adjustVelocity(v1-v0, Δt)
        else:
            yield from self.continueAtSameSpeed(10)
    else:
        yield from self.continueAtSameSpeed(10)

    self.rec.stopRecording(self)

def crash(self, other):

    def recordCrash(v):
        v.rec.record(v, 'crash')
        v.running = False
        v.crashed = True
        # stop anything you are currently doing...
        v.interruptProcess()
        v.dx0 = 0
        v.ddx0 = 0
        v.dddx0 = 0

    if self.running:
        if self.traceCrash:
            self.trace(f"Crashed into v{other.id:d} at x={self.x0:7.1f}m")
            recordCrash(self)
        if other.running:
            recordCrash(other)

def emergencyBraking(self, v):

    def emergencyBrakingProcess(v):

        if self.traceBraking:
            self.trace(f"Braking from v={self.dx0:4.1f}m/s to {v:4.1f}m/s"

)

        self.rec.record(self, 'brake')

```

```

minΔt = 0.2
self.dddx0 = (self.a_brake-self.ddx0)/minΔt
yield self.env.timeout(minΔt)

self.updateOnly()
self.dddx0=0
self.ddx0=self.a_brake
v = min(v, self.dx0-2)
    # the brake time estimate is for perfect timing for
    # autonomous cars. For manual driving leave out the
    # -minΔt/2 or use a random element.
Δt = max(0.5, (v-self.dx0)/self.ddx0 - minΔt/2)
yield self.env.timeout(Δt)

self.updateOnly()
self.dddx0 = -self.ddx0/minΔt
yield self.env.timeout(minΔt)

self.updateOnly()
self.ddx0 = 0
self.dddx0 = 0
self.rec.record(self, 'brake end')

if self.traceBraking:
    self.trace(f"Braking end v={self.dx0:4.1f}m/s")

## The 'braking' bit prevents the interruption of an emergency braking process
self.braking = True
self.processRef = self.env.process(emergencyBrakingProcess(v))
try:
    yield self.processRef
except simpy.Interrupt:
    if self.traceInterrupt or self.traceBraking:
        self.trace(f"Braking interrupted at v={self.dx0:4,.1f}m/s")
    pass
self.processRef = None
self.braking = False

def changeLane(self, inFront, direction, Δt):

    def changeLaneProcess(oldLane, newlane, Δt, trace=True):
        # self.updateOnly()
        if trace and self.traceOvertaking and inFront is not None and direction=='fast':
            other = f"v{inFront.id:d} " if inFront is not None else ""
            self.trace(f"Overtaking {other:s} at x={self.x0:7,.1f}m")

        self.rec.record(self, 'change '+direction)
        self.oldLane = oldLane
        newLane.enter(self, pos=self.pos, laneChange=True)
        self.ddx0 = 1
        self.dddx0 = 0
        yield self.env.timeout(Δt)

    self.updateOnly()
    if not self.running:

```



```

        return
        currentLane = self.lane
        self.oldLane.leave(self, laneChange=True)
        self.lane = currentLane
        self.oldLane = None
        self.ddx0 = 0
        self.dddx0 = 0
        self.rec.record(self, 'done change '+direction)

        if trace and self.traceOvertaking and direction=='slow':
            self.trace(f"Overtaking done return to slow lane at x={self.x
0:7,.1f}m")
            # self.updateOnly()

        ## keep record of current lane, as in case of aborting
        ## the lane change
        ## when interrupted go back into original lane
        self.changingLane = True
        self.updateOnly()
        oldLane = self.lane
        newLane = self.lane.getLane(direction)
        try:
            self.processRef = self.env.process(changeLaneProcess(oldLane, newL
ane, Δt))
            yield self.processRef
            self.processRef = None
        except simpy.Interrupt:
            if self.traceInterrupt and self.traceOvertaking:
                self.trace(f"Overtaking interrupted at x={self.x0:7,.1f}m")
            # if interrupted go quickly back into old lane
            # but this is not interruptible
            self.updateOnly()
            # it is possible that there was an intermittent change lane event
            while self.lane != newLane and newLane is not None:
                newLane = newLane.next
                oldLane = oldLane.next
            self.processRef = None
            self.env.process(changeLaneProcess(newLane, oldLane, Δt/4, trace=F
alse))
            self.changingLane = False

        # smoothly adjust velocity by Δv over the time Δt
        def adjustVelocity(self, Δv, Δt):

            # smoothly adjust velocity by Δv over the time Δt
            def adjustVelocityProcess():

                self.updateOnly()

                if self.traceAdjustVelocity:
                    self.trace(f"Adjusting Velocity from v={self.dx0:4,.1f}m/s by
Δv={Δv:4,.1f}m/s over {Δt:4,.1f}s")

                minΔt = 0.1*Δt
                a = Δv/(Δt-minΔt)
                tt = Δt-2*minΔt

```

```

self.dddx0 = (a-self.ddx0)/minΔt
yield self.env.timeout(minΔt)

self.updateOnly()
self.dddx0 = 0
self.ddx0 = a
yield self.env.timeout(tt)

self.updateOnly()
self.dddx0 = -a/minΔt
yield self.env.timeout(minΔt)

self.updateOnly()
self.dddx0 = 0
self.ddx0 = 0

if self.traceAdjustVelocity:
    self.trace(f"Adjusted Velocity to v={self.dx0:4,.1f}m/s")

# start process
self.current_target = self.dx0 + Δv
self.processRef = self.env.process(adjustVelocityProcess())
try:
    # wait for the process to finish
    yield self.processRef
except simpy.Interrupt:
    # in case this has been interrupted
    if self.traceInterrupt:
        self.trace(f"Adjusting Velocity interrupted at v={self.dx0:4,.1f}m/s")
    pass
self.current_target = None
self.processRef = None

def continueAtSameSpeed(self, Δt):

    def continueAtSameSpeedProcess():
        # don't change the current velocity
        self.dddx0 = 0
        self.ddx0 = 0
        yield self.env.timeout(Δt)

    # start process
    self.processRef = self.env.process(continueAtSameSpeedProcess())
    try:
        # wait for the process to finish
        yield self.processRef
    except simpy.Interrupt:
        # in case this has been interrupted
        if self.traceInterrupt:
            self.trace(f"Constant Velocity interrupted at v={self.dx0:4,.1f}m/s")
        pass
    self.processRef = None

def interruptProcess(self):
    if self.processRef is not None and self.processRef.is_alive:

```

```
self.processRef.interrupt('There are more important things to d  
o...')
```

## Property Surround

In [8]: **class** Surround:

```
    def __init__(self, vehicle):

        # For each of the directions None means that there is no
        # vehicle in the immediate vicinity.
        # We initialise to a 'safe' value which can be easily detected
        # if something goes wrong

        self.vehicle = vehicle

        self.leftBack = None
        self.left = None
        self.leftFront = None
        self.back = None

        self.front = None
        self.rightBack = None
        self.right = None
        self.rightFront = None

        lane = vehicle.lane
        posFront = vehicle.pos
        posBack = vehicle.pos-vehicle.length
        if lane is not None:
            self.lane = lane
            self.front = lane.inFront(posFront, self.vehicle.far_away_in_front
)

            self.back = lane.behind(posBack, self.vehicle.far_away_in_back)

            self.rightLane = lane.right
            if self.rightLane is not None:
                if vehicle.oldLane == lane.right:
                    # drifting left
                    self.right = vehicle
                    self.rightFront = self.rightLane.inFront(posFront, self.vehicle.far_away_in_front)
                    self.rightBack = self.rightLane.behind(posBack, self.vehicle.far_away_in_back)
                else:
                    right = self.rightLane.between(posBack-10, posFront+10)
                    if len(right)==0:
                        # self.right = None
                        self.rightFront = self.rightLane.inFront(posFront+10, self.vehicle.far_away_in_front)
                        self.rightBack = self.rightLane.behind(posBack-10, self.vehicle.far_away_in_back)
                    else:
                        self.right = right[0]
                        # self.rightFront = None
                        # self.rightBack = None

            self.leftLane = lane.left
            if self.leftLane is not None:
                if vehicle.oldLane == lane.left:
                    # drifting right
```

```

        self.left = vehicle
        self.leftFront = self.leftLane.inFront(posFront, self.vehicle.far_away_in_front)
        self.leftBack = self.leftLane.behind(posBack, self.vehicle.far_away_in_back)
    else:
        left = self.leftLane.between(posBack-10, posFront+10)
        if len(left)==0:
            # self.left = None
            self.leftFront = self.leftLane.inFront(posFront+10, self.vehicle.far_away_in_front)
            self.leftBack = self.leftLane.behind(posBack-10, self.vehicle.far_away_in_back)
        else:
            self.left = left[0]
            # self.leftFront = None
            # self.leftBack = None

    if vehicle.traceSurround:

        def s(vehicle):
            if vehicle is None:
                return " "
            elif type(vehicle) is list:
                if len(vehicle)==1:
                    return s(vehicle[0])
                else:
                    res = "["
                    for v in vehicle:
                        if len(res)>1:
                            res += ','
                        res+=s(v)
                    res += "]"
                    return res
            else:
                return f"{vehicle.id:d}"

        print(f"surround t={self.vehicle.env.now:6.2f} " +
              "| " +
              ("" if self.leftLane is None else
               f"|{s(self.leftBack):s}>{s(self.left):s}>{s(self.leftFront):s}" +
               f"|{s(self.back):s}>{s(self.vehicle):s}>{s(self.front):s}" +
               ("" if self.rightLane is None else
                f"{s(self.rightBack):s}>{s(self.right):s}>{s(self.rightFront):s}" +
                "|") +
              "| " +
              )

```

## Recorder

In [9]: **class Recorder:**

```
    def __init__(self, startTime=0, stopTime=0, timeStep=1):

        global VEHICLE_ID, LANE_ID
        VEHICLE_ID = 0
        LANE_ID = 0

        self.env = simpy.Environment()
        self.ps = []
        self.startTime = startTime
        self.stopTime = stopTime
        self.timeStep = timeStep
        self.data = pd.DataFrame(columns=['t', 'x', 'v', 'a', 'id', 'lane', 'oldLane', 'pos', 'event', 'Vehicle'])

        # runs the simulation
    def run(self):
        self.env.process(self.process())
        self.env.run(self.stopTime+self.timeStep)

    def process(self):
        yield self.env.timeout(self.startTime-self.env.now)
        while self.env.now <= self.stopTime:
            self.record()
            yield self.env.timeout(self.timeStep)

    def startRecording(self, p):
        self.ps.append(p)
        self.record(p, event='start')

    def stopRecording(self, p):
        self.ps.remove(p)

    def record(self, p=None, event='timer'):
        if p is not None:
            if p.updateOnly() or event!='timer':
                laneId = -1 if p.lane is None else p.lane.id
                oldLaneId = -1 if p.oldLane is None else p.oldLane.id
                ix = len(self.data)
                self.data.loc[ix]=[self.env.now, p.x0, p.dx0, p.ddx0, p.id, \
                                laneId, oldLaneId, p.pos, event, p.VEHICLE_
MODEL]

                if event=='timer':
                    p.update()
            else:
                for p in self.ps:
                    self.record(p, event)

        ## additional code: record lane information
    def recordLane(self, lane):
        ix = len(self.data)
        self.data.loc[ix]=[0, 0, 0, 0, 0, lane.id, -1, lane.length, 'lane info', 'No vehicle yet']

        ## additional code: record lane information
```

```

def getLaneLength(self, laneId):
    lanes = self.data[self.data.event=='lane info']
    lane = lanes[lanes.lane==laneId]
    return lane.pos.iloc[0]

def saveData(self, filename):
    self.data.to_csv(filename, index=False)

def getData(self):
    return self.data.copy(deep=True)

def getEvents(self):
    return self.data[self.data.event!='timer'].copy(deep=True)

## new code: computes traffic flow in vehicles/h at the end of a given lane
e
## based on 'Leave Lane' events proper (i.e. excluding overtaking)
def flow(self, lane):
    df = self.data[self.data.event=='leave lane']
    df = df[df.lane==lane]
    if len(df)>1:
        # compensate for lane filling late or early running dry
        f = (len(df)-1)*3600/(df.t.max()-df.t.min())
        return round(f, 2)
    else:
        return 0

## new code: computes the average travelling time through a lane segment
def avgTravelTime(self, laneId):
    d0 = self.data[self.data.event=='enter lane']
    d0 = d0[d0.lane==laneId]
    d1 = self.data[self.data.event=='leave lane']
    d1 = d1[d1.lane==laneId]
    times = []
    id0 = d0.id.unique()
    id1 = d1.id.unique()
    for id in id0:
        t0 = d0.t[d0.id==id].min()
        if id in id1:
            t1 = d1.t[d1.id==id].max()
            times += [ t1-t0 ]
    avg = 0
    if len(times)>0:
        avg = round(sum(times)/len(times), 2)
    return avg

def avgSpeed(self, laneId):
    return round(3.6*self.getLaneLength(laneId)/self.avgTravelTime(laneId
),2)

## new code: computes traffic density in vehicles/km for a given lane
## at a given moment in time. When no time is specified it returns a
## list of traffic densities over time.
def density(self, laneId, time=None):
    timerEvents = self.data[self.data.event=='timer']
    times = timerEvents.t.unique()

```

```

laneEvents = timerEvents[timerEvents.lane==laneId]
laneLength = self.getLaneLength(laneId)

if time is None:
    densities = []
    for t in times:
        events = laneEvents[laneEvents.t==t]
        d = len(events)*1000/laneLength
        densities.append(round(d,2))
    return sum(densities)/len(densities)

# find the timestamp nearest to the requested time
if time in times:
    t = time
else:
    # take the nearest point in time
    diff = list((times-time)**2)
    t = times[diff.index(min(diff))]
events = laneEvents[laneEvents.t==t]
d = len(events)*1000/laneLength
return round(d,2)

def plot(self, x, y,
        vehicles=None, style='', lw=1, decoration=True,
        x0=None, x1=None, y0=None, y1=None, fillColor=None,
        xmin=None, xmax=None, ymin=None, ymax=None):
    columns = ['t', 'x', 'v', 'a']
    labels = ['Time [s]', 'Position [m]', 'Velocity [m/s]', 'Acceleration
[m/s2']
    xindex = columns.index(x)
    yindex = columns.index(y)

    plt.figure(figsize=(5, 3), dpi=120)
    if xmin is not None and xmax is not None:
        plt.xlim((xmin, xmax))
    if ymin is not None and ymax is not None:
        plt.ylim((ymin, ymax))

    if vehicles is None:
        vehicles = list(self.data.id.unique())
    for id in vehicles:
        df = self.data[self.data.id==id]
        plt.plot(x, y, style, lw=lw, data=df)
        plt.xlabel(labels[xindex])
        plt.ylabel(labels[yindex])

        if not decoration:
            continue

        # use small red circle to indicate emergency braking
        dc = df[df.event=='brake']
        for i in range(len(dc)):
            X = dc.iloc[i, xindex]
            Y = dc.iloc[i, yindex]
            plt.plot([X], [Y], 'ro')

        db = df[df.event=='brake end']

```



```

for i in range(len(db)):
    X = db.iloc[i, xindex]
    Y = db.iloc[i, yindex]
    plt.plot([X], [Y], marker='o', mec='r', fillstyle='none')

# use black 'x' as crash indicator
dc = df[df.event=='crash']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], 'xk')

# use black Diamond to indicate that
# a vehicle ran out of track
dc = df[df.event=='end']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], 'Dk')

# use black right pointing full triangle
# to indicate that a vehicle started
# changing into the fast lane
dc = df[df.event=='change fast']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], '>k')

# use black right pointing hollow triangle
# to indicate that a vehicle has finished
# changing into the fast lane
dc = df[df.event=='done change fast']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], marker='>', mec='k', fillstyle='none')

# use black left pointing full triangle
# to indicate that a vehicle started
# changing into the slow lane
dc = df[df.event=='change slow']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], '<k')

# use black left pointing hollow triangle
# to indicate that a vehicle has finished
# changing into the slow lane
dc = df[df.event=='done change slow']
for i in range(len(dc)):
    X = dc.iloc[i, xindex]
    Y = dc.iloc[i, yindex]
    plt.plot([X], [Y], marker='<', mec='k', fillstyle='none')

```

```

# fill area with background color

```

```
if fillColor is not None:
    if x0 is None:
        x0=self.data[x].min()
    if x1 is None:
        x1=self.data[x].max()
    if y0 is None:
        y0=self.data[y].min()
    if y1 is None:
        y1=self.data[y].max()
    plt.fill_between( [x0, x1], [y0, y0], [y1, y1], color=fillColor)

plt.grid(True)
```

## Testing the functionality

```

In [10]: import random
VMAX = 120/3.6

N_l = 10 # number of vehicles in the left lane
IAT_l = 3 # average interarrival time left lane

N_c = 10 # number of vehicles in the central lane
IAT_c = 3 # average interarrival time central lane

N_r = 10 # number of vehicles in the right lane
IAT_r = 3 # average interarrival time right lane

random.seed(13)

iat_l = [ rv(IAT_l, delta=0.4*IAT_l) for i in range(N_l) ]
iat_r = [ rv(IAT_r, delta=0.4*IAT_r) for i in range(N_r) ]
iat_c = [ rv(IAT_c, delta=0.4*IAT_c) for i in range(N_c) ]

rec = Recorder(0, 100, 1)

c = Lane(rec, 1000)
c1 = Lane(rec, 700)
c2 = Lane(rec, 300)
c3 = Lane(rec, 1000)

c.extend(c1)
c.extend(c2)
c.extend(c3)

r = c.widenRight()

l = Lane(rec, 1000)
l1 = Lane(rec, 700)
l.extend(l1)

mergeLane = Lane(rec, 300, merge='R')
l.extend(mergeLane)

c.attachLeft(l)

print("L:", l)
print("C:", c)
print("R:", r)


# fill left lane
t = 0
for i in range(N_l):
    t += iat_l[i]
    v = Vehicle(rec, startingLane=1, t0=t, dx0=VMAX, vmax=VMAX, a_max=2.5)

# fill centre lane
t = 0
for i in range(N_c):

```

```

t += iat_c[i]
v = Vehicle(rec, startingLane=c, t0=t, dx0=VMAX, vmax=VMAX,a_max=3)

# fill right lane
t = 0
for i in range(N_r):
    t += iat_r[i]
    v = Vehicle(rec, startingLane=r, t0=t, dx0=VMAX, vmax=VMAX,a_max=5)

rec.run()

```

```

L: [08 x=0.0m l=1000.0m L:-- R:00]-[09 x=1000.0m l=700.0m L:-- R:--]-[10 x=1700.0m l=300.0m L:-- R:--]\
C: [00 x=0.0m l=1000.0m L:08 R:04]-[01 x=1000.0m l=700.0m L:-- R:05]-[02 x=1700.0m l=300.0m L:-- R:06]-[03 x=2000.0m l=1000.0m L:-- R:07]
R: [04 x=0.0m l=1000.0m L:00 R:--]-[05 x=1000.0m l=700.0m L:01 R:--]-[06 x=1700.0m l=300.0m L:02 R:--]-[07 x=2000.0m l=1000.0m L:03 R:--]

```

In [11]: `rec.getData()`

Out[11]:

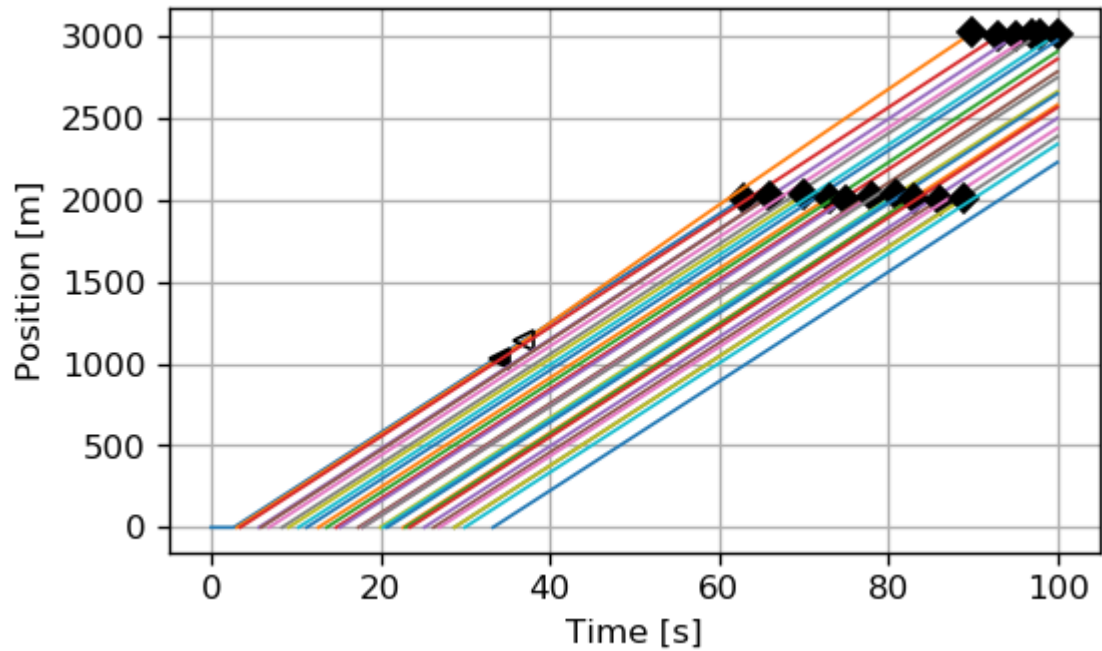
	t	x	v	a	id	lane	oldLane	pos	event	Vehicle
0	0	0	0	0	0	0	-1	1000	lane info	No vehicle yet
1	0	0	0	0	0	1	-1	700	lane info	No vehicle yet
2	0	0	0	0	0	2	-1	300	lane info	No vehicle yet
3	0	0	0	0	0	3	-1	1000	lane info	No vehicle yet
4	0	0	0	0	0	4	-1	1000	lane info	No vehicle yet
...	...	...	...	...	...	...	...	...	...	...
2495	100	2499.44	33.4965	0.00234936	28	7	-1	499.44	timer	car
2496	100	2438.59	33.464	0.00193117	17	3	-1	438.59	timer	car
2497	100	2388.38	33.72	0.00585171	29	7	-1	388.38	timer	car
2498	100	2340.25	33.5047	0.00265042	18	3	-1	340.25	timer	car
2499	100	2229.82	33.5453	0.00341758	19	3	-1	229.82	timer	car

2500 rows × 10 columns

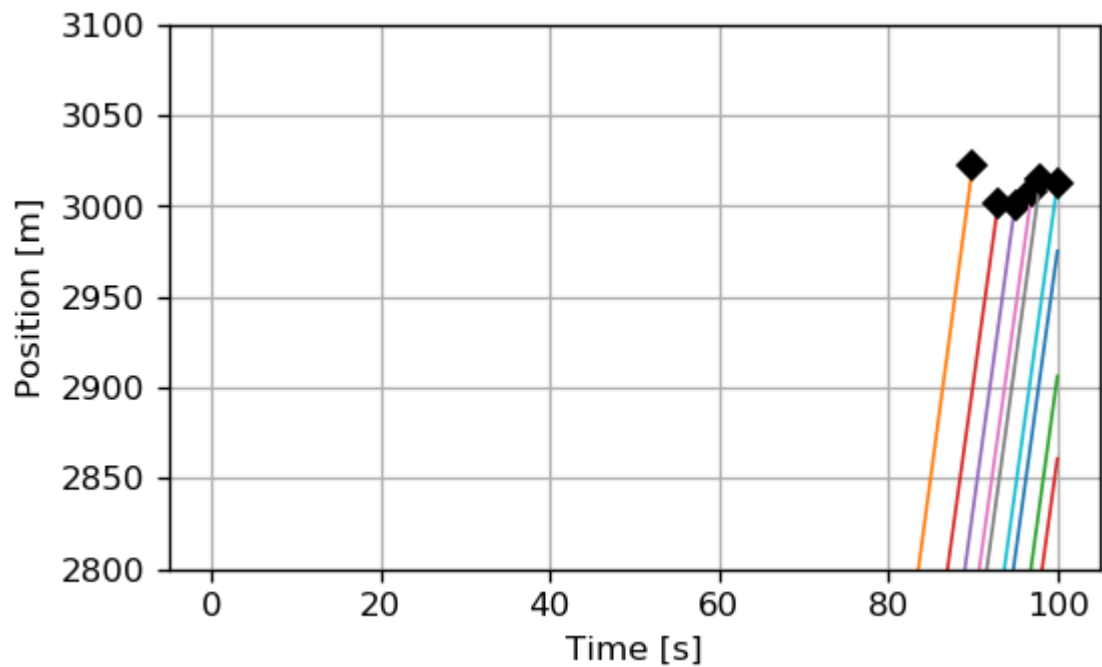
In [12]: `rec.data['Vehicle'].unique()`

Out[12]: `array(['No vehicle yet', 'car'], dtype=object)`

```
In [13]: rec.plot('t', 'x')
```



```
In [14]: rec.plot('t', 'x', ymin=2800, ymax=3100)
```



## Traffic Flow in veh/h

The traffic flow at the end of lane segments for the **left lane**:

```
In [15]: rec.flow(6), rec.flow(7) #rec.flow(4)
```

```
Out[15]: (1252.17, 1200.0)
```

The traffic flow at the end of lane segments for the **right lane**:

```
In [16]: rec.flow(3), rec.flow(4), rec.flow(5)
```

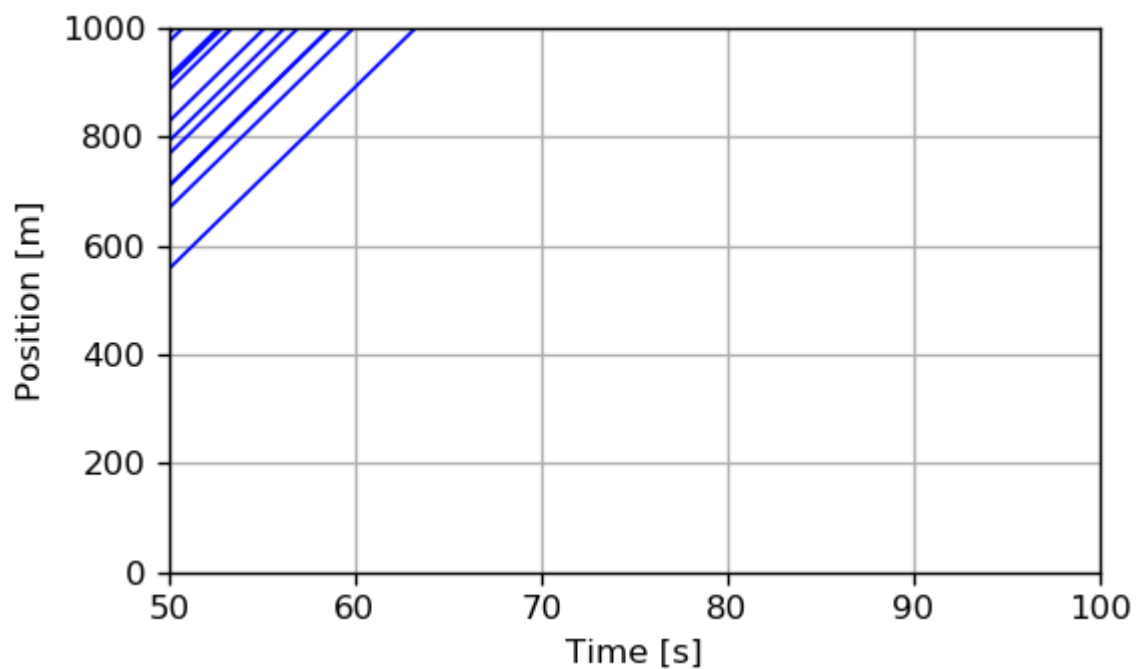
```
Out[16]: (1080.0, 1296.0, 1252.17)
```

The traffic flow at the end of lane segments for the **centre lane**:

```
In [17]: rec.flow(0), rec.flow(1), rec.flow(2)
```

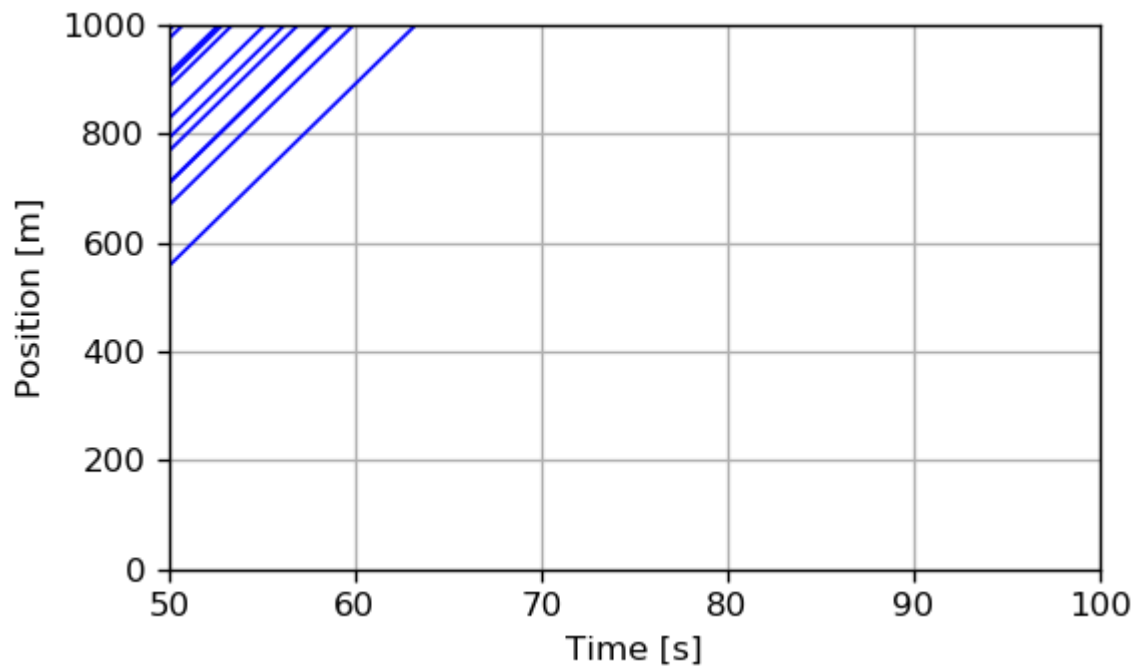
```
Out[17]: (1080.0, 1125.0, 1090.91)
```

```
In [18]: rec.plot('t', 'x', xmin=50, xmax=100, ymin=0, ymax=1000, style='b')
```



**Traffic Density in veh/km**

```
In [19]: rec.plot('t', 'x', xmin=50, xmax=100, ymin=0, ymax=1000, style='b')
```



```
In [20]: #The statistics reports:
print(rec.density(0, 50) + rec.density(1, 50)+rec.density(2, 50))
print(rec.density(3, 50) + rec.density(4, 50)+rec.density(5, 50))
print(rec.density(6, 50) + rec.density(7, 50))
```

```
13.57
11.57
0.0
```

## Average Travel Times in s

```
In [21]: rec.avgTravelTime(0)
```

```
Out[21]: 30.38
```

## Average Speed in km/h

```
In [22]: rec.avgSpeed(0)
```

```
Out[22]: 118.5
```

## Fundamental Law

```
In [23]: rec.density(0, 50)*rec.avgSpeed(0) + rec.density(3, 50)*rec.avgSpeed(3)
```

```
Out[23]: 592.5
```

```
In [ ]:
```

## Testing Simulation with different Vehicle types

Case 1

1000 Vehicles, 300 in left Lane, 400 in center lane and 300 in Right Lane

Inter-Arrival Time Distributions = 3 sec for each lane

Traffic Mix = 45% of "Car", 20% of "Electric Car", 35% of " heavy goods vehicles"

Motorway speed Limit Setting = 120Km/h = 120/3.6 m/s



```
In [24]: import random
VMAX = 120/3.6

N_l = 300 # number of vehicles in the left lane
IAT_l = 3 # average interarrival time left lane

N_c = 400 # number of vehicles in the central lane
IAT_c = 3 # average interarrival time central lane

N_r = 300 # number of vehicles in the right lane
IAT_r = 3 # average interarrival time right lane

random.seed(13)

iat_l = [ rv(IAT_l, delta=0.4*IAT_l) for i in range(N_l) ]
iat_r = [ rv(IAT_r, delta=0.4*IAT_r) for i in range(N_r) ]
iat_c = [ rv(IAT_c, delta=0.4*IAT_c) for i in range(N_c) ]

rec = Recorder(0, 100, 1)

c = Lane(rec, 1700)
c1 = Lane(rec, 300)
c2= Lane(rec, 1000)
c.extend(c1)
c.extend(c2)

r = Lane(rec, 1700)
r1 = Lane(rec, 300)
r2= Lane(rec, 1000)
r.extend(r1)
r.extend(r2)
c.attachRight(r)

#r = c.widenRight()
l = Lane(rec, 1700)
mergeLane = Lane(rec, 300, merge='R')
l.extend(mergeLane)
c.attachLeft(l)

# c = Lane(rec, 1000)
# c1 = Lane(rec, 700)
# c2= Lane(rec, 300)
# c3= Lane(rec, 1000)

# c.extend(c1)
# c.extend(c2)
# c.extend(c3)

# r = Lane(rec, 1000)
```

```

# r1 = Lane(rec, 700)
# r2 = Lane(rec, 300)
# r3 = Lane(rec, 1000)

# r.extend(r1)
# r.extend(r2)
# r.extend(r3)

# c.attachRight(r)

# #r = c.widenRight()

# L = Lane(rec, 1000)
# l1 = Lane(rec, 700)
# L.extend(l1)

# mergeLane = Lane(rec, 300, merge='R')
# L.extend(mergeLane)

# c.attachLeft(L)

print("L:", l)
print("C:", c)
print("R:", r)

#for right
t=0
for i in range(N_r):
    t += iat_r[i]
    v = Vehicle(rec, startingLane=r, t0=t, dx0=VMAX, vmax=VMAX)

t = 0
# fill left lane
for i in range(N_l):
    t += iat_l[i]
    # v = Vehicle(rec, startingLane=l, t0=t, dx0=VMAX, vmax=VMAX, a_max=2.5)

    r=random.random()
    if r<=0.2:#electric car
        v = Vehicle(rec, startingLane=1, t0=t, dx0=VMAX, vmax=VMAX, a_max=2.5,
VEHICLE_MODEL='electric car')
    elif r<=0.55:
        v = Vehicle(rec, startingLane=1, t0=t, dx0=VMAX, vmax=VMAX, a_max=2.5,
VEHICLE_MODEL='HGV')
    else:
        v = Vehicle(rec, startingLane=1, t0=t, dx0=VMAX, vmax=VMAX, a_max=2.5)

```

```

# fill centre lane
t=0
for i in range(N_c):
    t += iat_c[i]
    # v = Vehicle(rec, startingLane=c, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.5)

    r=random.random()
    if r<=0.2:
        v = Vehicle(rec, startingLane=c, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.5,
VEHICLE_MODEL='electric car')
    elif r<=0.55:
        v = Vehicle(rec, startingLane=c, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.5,
VEHICLE_MODEL='HGV')
    else:
        v = Vehicle(rec, startingLane=c, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.5)

# r=random.random()
# if r<=0.2:
#     v = Vehicle(rec, startingLane=r, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.
5, VEHICLE_MODEL='electric car')
# elif r<=0.4:
#     v = Vehicle(rec, startingLane=r, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.
5, VEHICLE_MODEL='HGV')
# else:
#     v = Vehicle(rec, startingLane=r, t0=t, dx0=VMAX, vmax=VMAX,a_max=2.
5)

rec.run()

```

```

L: [06 x=0.0m l=1700.0m L:-- R:00]-[07 x=1700.0m l=300.0m L:-- R:--]\
C: [00 x=0.0m l=1700.0m L:06 R:03]-[01 x=1700.0m l=300.0m L:-- R:--]-[02 x=20
00.0m l=1000.0m L:-- R:--]
R: [03 x=0.0m l=1700.0m L:00 R:--]-[04 x=1700.0m l=300.0m L:-- R:--]-[05 x=20
00.0m l=1000.0m L:-- R:--]

```

In [25]: `rec.getData()`

Out[25]:

	t	x	v	a	id	lane	oldLane	pos	event	Vehicle
0	0	0	0	0	0	0	-1	1700	lane info	No vehicle yet
1	0	0	0	0	0	1	-1	300	lane info	No vehicle yet
2	0	0	0	0	0	2	-1	1000	lane info	No vehicle yet
3	0	0	0	0	0	3	-1	1700	lane info	No vehicle yet
4	0	0	0	0	0	4	-1	300	lane info	No vehicle yet
...	...	...	...	...	...	...	...	...	...	...
4969	100	108.48	33.3357	0.00145737	31	3	-1	108.48	timer	car
4970	100	107.61	33.3335	0.000125043	331	6	-1	107.61	timer	electric car
4971	100	35.16	33.3338	0.00095154	632	0	-1	35.16	timer	car
4972	100	31.59	33.3333	9.8083e-06	32	3	-1	31.59	timer	car
4973	100	13.49	33.3334	0.000263778	332	6	-1	13.49	timer	car

4974 rows × 10 columns

In [ ]:

## Statistics of self organising motorway scenarios

### Before Merging at 1700m

```

In [26]: # rec.flow(6)+rec.flow(7)
# rec.flow(0)+ rec.flow(1)+ rec.flow(2)
# rec.flow(3)+ rec.flow(4)+ rec.flow(5)

# The traffic Volume at the end of lane segments for the different lanes (veh/
hr):

print("***** After 1700m (1KM)*****")
print("The traffic Volume at 1700m the left lane : ", rec.flow(6))
print(" The traffic Volume at 1700m the right lane :", rec.flow(3))
print(" The traffic Volume at 1700m the centre lane", rec.flow(0))
print(" \n The traffic Volume at 1700m in all lane", rec.flow(0)+ rec.flow(3)+
rec.flow(6))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print("The traffic density at 1700m the left lane : ", rec.density(6, 50))
print(" The traffic density at 1700m the right lane :", rec.density(3, 50))
print(" The traffic density at 1700m the centre lane", rec.density(0, 50))
print(" \nThe traffic density at 1700m in all lane", rec.density(6, 50)+ rec.d
ensity(0, 50)+ rec.density(3, 50))

print("\n -----")
# Average travel time:

print("Average Travel travel at 1700m the left lane :", rec.avgTravelTime(6))
print("Average Travel travel at 1700m the right lane :", rec.avgTravelTime(3))
print("Average Travel travel at 1700m the centre lane :", rec.avgTravelTime(0
))
print("\nAverage Travel travel at 1700m in all lane :", (rec.avgTravelTime(0)+
rec.avgTravelTime(6)+ rec.avgTravelTime(3))/3)

print("\n -----")

# Average Speed

print("Average speed at the 1700m the left lane :", rec.avgSpeed(6))
print("Average speed at the 1700m the right lane :", rec.avgSpeed(3))
print("Average speed at the 1700m the centre lane :", rec.avgSpeed(0))
print("Average speed at the 1700m the all lane :", (rec.avgSpeed(0)+ rec.avgSp
eed(3)+ rec.avgSpeed(6))/3)

```

\*\*\*\*\* After 1700m (1KM)\*\*\*\*\*

The traffic Volume at 1700m the left lane : 1250.28

The traffic Volume at 1700m the right lane : 1145.45

The traffic Volume at 1700m the centre lane 1228.8

The traffic Volume at 1700m in all lane 3624.5299999999997

-----  
The traffic density at 1700m the left lane : 10.0

The traffic density at 1700m the right lane : 8.82

The traffic density at 1700m the centre lane 9.41

The traffic density at 1700m in all lane 28.23

-----  
Average Travel travel at 1700m the left lane : 51.21

Average Travel travel at 1700m the right lane : 51.33

Average Travel travel at 1700m the centre lane : 51.31

Average Travel travel at 1700m in all lane : 51.28333333333334

-----  
Average speed at the 1700m the left lane : 119.51

Average speed at the 1700m the right lane : 119.23

Average speed at the 1700m the centre lane : 119.27

Average speed at the 1700m the all lane : 119.33666666666666

**After Merging 3 lane to 2 lane at 2000m**

```

In [27]: # The traffic Volume at the end of lane segments for the different lanes (veh/
hr):

print("***** After 2000m (*****
\n")
print("The traffic Volume at 2000m the left lane :", rec.flow(7))
print(" The traffic Volume at 2000m the right lane :", rec.flow(4))
print(" The traffic Volume at 2000m the centre lane", rec.flow(1))
print(" \n The traffic Volume at 2000m in all lane", rec.flow(7)+ rec.flow(1)+
rec.flow(4))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print("The traffic density at 2000m the left lane :", rec.density(7, 100))
print(" The traffic density at 2000m the right lane :", rec.density(4, 100))
print(" The traffic density at 2000m the centre lane", rec.density(1, 100))
print(" \nThe traffic density at 2000m in all lane", rec.density(1, 100)+ rec.
density(7, 100)+ rec.density(4, 100))

print("\n -----")
# Average travel time:

print("Average Travel travel at 2000m the left lane :", rec.avgTravelTime(7))
print("Average Travel travel at 2000m the right lane :", rec.avgTravelTime(4))
print("Average Travel travel at 2000m the centre lane :", rec.avgTravelTime(1
))
print("\nAverage Travel travel at 2000m in all lane :", (rec.avgTravelTime(1)+
rec.avgTravelTime(4)+ rec.avgTravelTime(7))/3)

print("\n -----")

# Average Speed

print("Average speed at the 2000m the left lane :", rec.avgSpeed(7))
print("Average speed at the 2000m the right lane :", rec.avgSpeed(4))
print("Average speed at the 2000m the centre lane :", rec.avgSpeed(1))
print("Average speed at the 2000m the all lane :", (rec.avgSpeed(1)+ rec.avgSp
eed(4)+ rec.avgSpeed(7))/3)

```

\*\*\*\*\* After 2000m (\*\*\*\*\*

The traffic Volume at 2000m the left lane : 1264.86

The traffic Volume at 2000m the right lane : 1164.71

The traffic Volume at 2000m the centre lane 1200.0

The traffic Volume at 2000m in all lane 3629.5699999999997

-----  
The traffic density at 2000m the left lane : 10.0

The traffic density at 2000m the right lane : 10.0

The traffic density at 2000m the centre lane 10.0

The traffic density at 2000m in all lane 30.0

-----  
Average Travel travel at 2000m the left lane : 8.96

Average Travel travel at 2000m the right lane : 9.09

Average Travel travel at 2000m the centre lane : 9.02

Average Travel travel at 2000m in all lane : 9.023333333333333

-----  
Average speed at the 2000m the left lane : 120.54

Average speed at the 2000m the right lane : 118.81

Average speed at the 2000m the centre lane : 119.73

Average speed at the 2000m the all lane : 119.69333333333334

In [ ]:

**At the end of the motorway section at 3000m**



```

In [28]: # The traffic Volume at the end of lane segments for the different lanes (veh/
hr):

print("***** After 3000m (*****
\n")

print(" The traffic Volume at 3000m the right lane :", rec.flow(5))
print(" The traffic Volume at 3000m the centre lane", rec.flow(2))
print(" \n The traffic Volume at 3000m in all lane", rec.flow(2)+ rec.flow(5))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print(" The traffic density at 3000m the right lane :", rec.density(5, 50))
print(" The traffic density at 3000m the centre lane", rec.density(2, 50))
print(" \nThe traffic density at 3000m in all lane", rec.density(5, 50)+ rec.d
ensity(2, 50))

print("\n -----")
# Average travel time:

print("Average Travel travel at 3000m the right lane :", rec.avgTravelTime(5))
print("Average Travel travel at 3000m the centre lane :", rec.avgTravelTime(2
))
print("\nAverage Travel travel at 3000m in all lane :", (rec.avgTravelTime(5)+
rec.avgTravelTime(2))/2)

print("\n -----")

# Average Speed

print("Average speed at the 3000m the right lane :", rec.avgSpeed(5))
print("Average speed at the 3000m the centre lane :", rec.avgSpeed(2))
print("Average speed at the 3000m the all lane :", (rec.avgSpeed(5)+ rec.avgSp
eed(2))/2)

```

\*\*\*\*\* After 3000m (\*\*\*\*\*

The traffic Volume at 3000m the right lane : 1200.0

The traffic Volume at 3000m the centre lane 1028.57

The traffic Volume at 3000m in all lane 2228.5699999999997

-----  
The traffic density at 3000m the right lane : 0.0

The traffic density at 3000m the centre lane 0.0

The traffic density at 3000m in all lane 0.0

-----  
Average Travel travel at 3000m the right lane : 29.67

Average Travel travel at 3000m the centre lane : 29.67

Average Travel travel at 3000m in all lane : 29.67

-----  
Average speed at the 3000m the right lane : 121.33

Average speed at the 3000m the centre lane : 121.33

Average speed at the 3000m the all lane : 121.33

## Part 2 Vehicle Type with Driver behaviour

In [ ]:

```
In [29]: free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
quantiles = np.cumsum([0, 0.002, 0.015, 0.025, 0.178, 0.372, 0.390, 0.119
, 0.148, 0.03, 0.001])
def random_speed():
    u = random.random() # uniformly distributed random number generated between
0 and 1
    for i in range(len(quantiles)):
        if u<quantiles[i+1]:
            p = (u-quantiles[i])/(quantiles[i+1]-quantiles[i])
            return free_speed[i]*p+free_speed[i+1]*(1-p)
```

```
In [30]: random.seed(0)
speeds = [ random_speed() for i in range(210000)]
kernel = stats.gaussian_kde(speeds)
```

```

In [31]: v1 = np.arange(60, 170) #generate spread out from 60 170
q1 = [ kernel.integrate_box_1d(30, i) for i in v1 ]
def freeMotorwaySpeed():
    u = random.random() # generates uniformly distributed random number between 0 and 1
    for i in range(len(q1)):
        if u < q1[i+1]:
            p1 = (u-q1[i])/(q1[i+1]-q1[i])
            # return (free_speed[i+1]+free_speed[i])/2*p+(1-p)*(free_speed[i+1]+free_speed[i+2])/2
            return v1[i]*p1+v1[i+1]*(1-p1)

freeMotorwaySpeed()

```

Out[31]: 84.19903863508866

```

In [32]: free_speed_bins = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160]
free_speed_quantiles = np.cumsum([0, 0.006, 0.014, 0.052, 0.148, 0.27, 0.309, 0.143, 0.048, 0.01])

def free_speed_distribution():
    u = random.random() # generates uniformly distributed random number between 0 and 1
    for i in range(len(free_speed_quantiles)):
        if u < free_speed_quantiles[i+1]:
            p = (u-free_speed_quantiles[i])/(free_speed_quantiles[i+1]-free_speed_quantiles[i])
            return free_speed_bins[i]*p+free_speed_bins[i+1]*(1-p)

free_speed_data = [ free_speed_distribution() for i in range(1200)]
free_speed_kernel = stats.gaussian_kde(free_speed_data)

free_speeds = np.arange(30, 191)
free_speed_cdf = [ free_speed_kernel.integrate_box_1d(30, i) for i in free_speeds ]

def random_free_speed():
    u = random.random() # generates uniformly distributed random number between 0 and 1
    for i in range(len(free_speeds)):
        if u < free_speed_cdf[i+1]:
            p = (u-free_speed_cdf[i])/(free_speed_cdf[i+1]-free_speed_cdf[i])
            return free_speeds[i]*p+free_speeds[i+1]*(1-p)

```

```

In [33]: speeds = [ random_free_speed() for i in range(100000) ]

```

```

In [34]: def VehiclePlusDriverType(HGV, electric, car, autonomous = 0, d_behaviour=1):
    w = random.random()

    if w <= autonomous:
        vdrivers = 'Human'
    else:
        vdrivers = 'auto'

    d = random.random()
    if d < d_behaviour:
        behaviour = 'normal'
    elif d > d_behaviour:
        behaviour = 'drunk'
    else:
        behaviour='rash'

    vFAR_AWAY_IN_FRONT = 200
    vFAR_AWAY_IN_BACK = 80

    u = random.random()
    if u <= HGV:
        vtype = 'HGV'
        vstartspeed = freeMotorwaySpeed()/3.6 ##### vstartspeed = freeMotorwaySpeed
Lorry()/3.6
        vlength = 15
        va_max = 0.96

        if vdrivers == 'Human':
            if behaviour== "drunk":
                # fixed 0.4 difference
                va_min = -1.28 + 0.125*random.random()
            elif behaviour == "normal":
                va_min = -0.88 + 0.125*random.random()
            elif behaviour == "rash":
                # fixed 0.25 difference
                va_min = -0.63 + 0.125*random.random()

        else:
            va_min = -0.88
            vFAR_AWAY_IN_FRONT = 200
            vFAR_AWAY_IN_BACK = 110

    elif u <= HGV + electric: #####?????
        vtype = 'Electric Car'
        vstartspeed = freeMotorwaySpeed()/3.6
        vlength = 6
        va_max = 2.47
        if vdrivers == 'Human':
            if behaviour== "drunk":
                va_min = -4.37 + 0.5*random.random()
            elif behaviour == "normal":
                va_min = -3.97 + 0.5*random.random()
            elif behaviour == "rash":
                va_min = -3.72 + 0.125*random.random()

```

```

else:
    va_min = -3.97
    vFAR_AWAY_IN_FRONT = 200
    vFAR_AWAY_IN_BACK = 80
else:
    vtype = 'Car'
    vstartspeed = freeMotorwaySpeed()/3.6
    vlength = 4
    va_max = 2.47
    if vdrivers == 'Human':
        if behaviour == "drunk":
            va_min = -2.15 + 0.4*random.random()
        elif behaviour == "normal":
            va_min = -2.55 + 0.4**random.random()
        elif behaviour == "rash":
            va_min = -2.8 + 0.125*random.random()

    else:
        va_min = -3.97
        vFAR_AWAY_IN_FRONT = 200
        vFAR_AWAY_IN_BACK = 80

    return vtype, vstartspeed, vlength, va_max, va_min, vFAR_AWAY_IN_FRONT, vFAR_AWAY_IN_BACK, vdrivers, behaviour

```

In [35]: SLOW\_CYCLE = 100

```

def randomIntervals(cycles):
    # return [ random.expovariate(1.0/SLOW_CYCLE)+10 for i in range(cycles) ]
    return [ max(0, random.normalvariate(SLOW_CYCLE, SLOW_CYCLE/3)) for i in range(cycles) ]

```

In [36]: `def cyc(): # random element to cycles`  
         cycles = 5 + round(5\*(random.random()))  
         return cycles  
cyc()

Out[36]: 10

In [37]: SPEED\_VARIATION = 0.05 *#To get an idea about the time intervals and the speed approached we look at the first few random values:*  
random.seed(13)

```

def randomSpeedVariation(vmax, cycles, cv=SPEED_VARIATION):
    return [ vmax + (-1)**i*abs(random.normalvariate(0, vmax*cv)) for i in range(cycles) ]

```

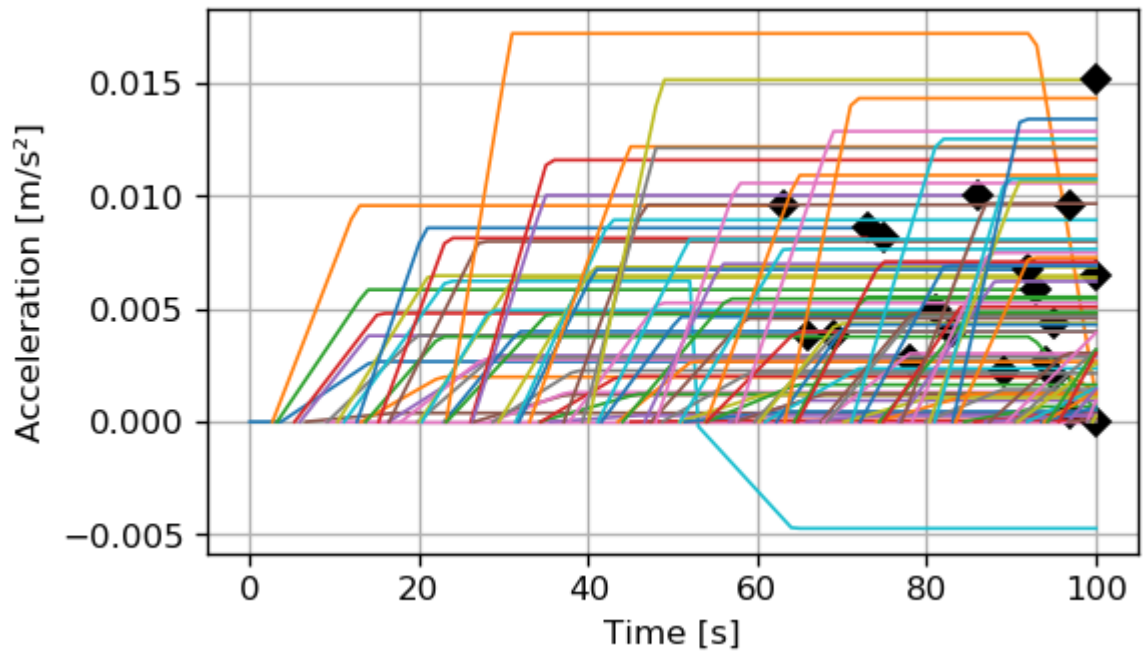
In [ ]:

In [ ]:

# Simulation of Part 2

## Case 1

In [38]: `rec.plot('t', 'a')`



In [ ]:

## Statistics of self organising motorway scenarios

### Before Merging at 1700m

In [39]: *# The traffic Volume at the end of lane segments for the different lanes (veh/hr):*

```
print("***** After 1700m (1KM)*****")
print("The traffic Volume at 1700m the left lane :", rec.flow(6))
print(" The traffic Volume at 1700m the right lane :", rec.flow(3))
print(" The traffic Volume at 1700m the centre lane", rec.flow(0))
print(" \n The traffic Volume at 1700m in all lane", rec.flow(0)+ rec.flow(3)+
rec.flow(6))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print("The traffic density at 1700m the left lane :", rec.density(6, 50))
print(" The traffic density at 1700m the right lane :", rec.density(3, 50))
print(" The traffic density at 1700m the centre lane", rec.density(0, 50))
print(" \nThe traffic density at 1700m in all lane", rec.density(6, 50)+ rec.d
ensity(0, 50)+ rec.density(3, 50))

print("\n -----")
# Average travel time:

print("Average Travel travel at 1700m the left lane :", rec.avgTravelTime(6))
print("Average Travel travel at 1700m the right lane :", rec.avgTravelTime(3))
print("Average Travel travel at 1700m the centre lane :", rec.avgTravelTime(0
))
print("\nAverage Travel travel at 1700m in all lane :", (rec.avgTravelTime(0)+
rec.avgTravelTime(6)+ rec.avgTravelTime(3))/3)

print("\n -----")
```

\*\*\*\*\* After 1700m (1KM)\*\*\*\*\*

The traffic Volume at 1700m the left lane : 1250.28

The traffic Volume at 1700m the right lane : 1145.45

The traffic Volume at 1700m the centre lane 1228.8

The traffic Volume at 1700m in all lane 3624.5299999999997

-----  
The traffic density at 1700m the left lane : 10.0

The traffic density at 1700m the right lane : 8.82

The traffic density at 1700m the centre lane 9.41

The traffic density at 1700m in all lane 28.23

-----  
Average Travel travel at 1700m the left lane : 51.21

Average Travel travel at 1700m the right lane : 51.33

Average Travel travel at 1700m the centre lane : 51.31

Average Travel travel at 1700m in all lane : 51.283333333333334

-----

**After Merging 3 lane to 2 lane at 2000m**



```

In [40]: # The traffic Volume at the end of lane segments for the different lanes (veh/
hr):

print("***** After 2000m (*****
\n")
print("The traffic Volume at 2000m the left lane :", rec.flow(7))
print(" The traffic Volume at 2000m the right lane :", rec.flow(4))
print(" The traffic Volume at 2000m the centre lane", rec.flow(1))
print(" \n The traffic Volume at 2000m in all lane", rec.flow(7)+ rec.flow(1)+
rec.flow(4))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print("The traffic density at 2000m the left lane :", rec.density(7, 100))
print(" The traffic density at 2000m the right lane :", rec.density(4, 100))
print(" The traffic density at 2000m the centre lane", rec.density(1, 100))
print(" \nThe traffic density at 2000m in all lane", rec.density(1, 100)+ rec.
density(7, 100)+ rec.density(4, 100))

print("\n -----")
# Average travel time:

print("Average Time travel at 2000m the left lane :", rec.avgTravelTime(7))
print("Average Time travel at 2000m the right lane :", rec.avgTravelTime(4))
print("Average Time travel at 2000m the centre lane :", rec.avgTravelTime(1))
print("\nAverage time travel at 2000m in all lane :", (rec.avgTravelTime(1)+ r
ec.avgTravelTime(4)+ rec.avgTravelTime(7))/3)

print("\n -----")

# Average Speed

print("Average speed at the 2000m the left lane :", rec.avgSpeed(7))
#print("Average speed at the 2000m the right Lane :", rec.avgSpeed(4))
#print("Average speed at the 2000m the centre Lane :", rec.avgSpeed(1))
#print("Average speed at the 2000m the all Lane :", (rec.avgSpeed(1)+ rec.avgS
peed(4)+ rec.avgSpeed(7))/3)

```

\*\*\*\*\* After 2000m (\*\*\*\*\*

The traffic Volume at 2000m the left lane : 1264.86

The traffic Volume at 2000m the right lane : 1164.71

The traffic Volume at 2000m the centre lane 1200.0

The traffic Volume at 2000m in all lane 3629.5699999999997

-----  
The traffic density at 2000m the left lane : 10.0

The traffic density at 2000m the right lane : 10.0

The traffic density at 2000m the centre lane 10.0

The traffic density at 2000m in all lane 30.0

-----  
Average Time travel at 2000m the left lane : 8.96

Average Time travel at 2000m the right lane : 9.09

Average Time travel at 2000m the centre lane : 9.02

Average time travel at 2000m in all lane : 9.023333333333333

-----  
Average speed at the 2000m the left lane : 120.54

In [ ]:

**At the end of the motorway section at 3000m**

```

In [41]: # The traffic Volume at the end of lane segments for the different lanes (veh/
hr):

print("***** After 3000m (*****
\n")

print(" The traffic Volume at 3000m the right lane :", rec.flow(5))
print(" The traffic Volume at 3000m the centre lane", rec.flow(2))
print(" \n The traffic Volume at 3000m in all lane", rec.flow(2)+ rec.flow(5))

print("\n -----")
# Traffic Density at the end of lane segments for the different lanes (veh/k
m):

print(" The traffic density at 3000m the right lane :", rec.density(5, 50))
print(" The traffic density at 3000m the centre lane", rec.density(2, 50))
print(" \nThe traffic density at 3000m in all lane", rec.density(5, 50)+ rec.d
ensity(2, 50))

print("\n -----")
# Average travel time:

print("Average Travel travel at 3000m the right lane :", rec.avgTravelTime(5))
print("Average Travel travel at 3000m the centre lane :", rec.avgTravelTime(2
))
print("\nAverage Travel travel at 3000m in all lane :", (rec.avgTravelTime(5)+
rec.avgTravelTime(2))/2)

print("\n -----")

# Average Speed

#print("Average speed at the 3000m the right Lane :", rec.avgSpeed(5))
#print("Average speed at the 3000m the centre lane :", rec.avgSpeed(2))
#print("Average speed at the 3000m the all lane :", (rec.avgSpeed(5)+ rec.avgS
peed(2))/2)

```

\*\*\*\*\* After 3000m (\*\*\*\*\*

The traffic Volume at 3000m the right lane : 1200.0

The traffic Volume at 3000m the centre lane 1028.57

The traffic Volume at 3000m in all lane 2228.5699999999997

-----  
The traffic density at 3000m the right lane : 0.0  
The traffic density at 3000m the centre lane 0.0

The traffic density at 3000m in all lane 0.0

-----  
Average Travel travel at 3000m the right lane : 29.67  
Average Travel travel at 3000m the centre lane : 29.67

Average Travel travel at 3000m in all lane : 29.67  
-----

In [42]: rec.saveData("Data\_x20192037\_priyanka\_simulation1\_120kmperhour.csv")

In [ ]:

In [ ]: