MSO_CA1-x19219997_FINAL_CODE_FILE

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3 Module: Modelling, Simulation and Optimization (CA-1)

4 Topic: Simulation of Traffic Flow to analyze the Vehicle bheaviour on a Multi-Lane Motorway using Simpy

Importing necessary packages

[488]:

```
import pandas as pd
import matplotlib.pyplot as plt
import scipy.stats as stats
import math
import numpy as np
import random
import simpy
import simpy.events as evt
```

Defining the ϵ for comparing the small distances in the traffic simulation

[344]:

```
  = 0.00001
def isZero(x):
    return abs(x)<
```

Defining global variables - Units are defined in mks system [Need to be included into the vehicle class for the second task]

[489]:

```
# Time tolerance: when at current speed difference a crash might occur within␣
 ↪that number of seconds
CRITICAL_TIME_TOLERANCE = 4  # [s]   #Could be changed later if desired
LANE_CHANGE_TIME = 3 # [s]     # Maximum time it takes for a vehicle to change␣
 ↪the lane
MIN_TIME_DIFF = 1      # Minimum difference in times to trigger overtaking

MIN_SPEED_DIFF = 2 # [m/s] min speed diff to trigger overtaking
```

```
CAR_LENGTH = 4 # [m]

FAR_AWAY_IN_FRONT = 200 # [m]  distance at which a car in front can be ignored
FAR_AWAY_IN_BACK = 80   # [m]  distance at which a car behind can be ignored
```

5 1. Lanes –Defines the construction of different lane segments

[490]:
```
# Assigning left lane as the slow lane and right lane as the fast lane
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
```

[491]:
```
LANE_ID = 0

class Lane:

    ## some additional code
    def __init__(self, length, speedLimit):

        global LANE_ID
        self.id = LANE_ID
        LANE_ID += 1

        self.length = length    # defines the lane length
        self.speedLimit = speedLimit    # defines the speed limit for the lane
        self.vehicles = []    # defines the vehicles on the lanes

        self.next = None     # for the next lane segment
        self.prev = None     # for the previous lane segment

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

    # defines generic str() method for Lanes
    # extends the method with list of vehicles on the lane
    def __str__(self):
        l = "" if self.left is None else f" L:{self.left.id:d}"
        r = "" if self.right is None else f" R:{self.right.id:d}"
        vs = "" if len(self.vehicles)==0 else " "
        for v in self.vehicles:
            vs += str(v)
        return f"[{self.id:d} {int(self.length):d}m"+l+r+vs+"]" + \
                    ("-" + str(self.next) if self.next is not None else "")

    def getLane(self, direction):        # this function defines the slow and fast lanes. Left lane is considered as the slow lane which is used by majority
        if direction=='slow':             # of the vehicles and the right lane is considered as the fast lane which is used by only a small fraction of the
            return self.left              # vehicles.
        elif direction=='fast':
            return self.right
        else:
            return None

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

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

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

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

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

    ## additional code
    ## new generalised access method needed to calculate sideway view
    ## returns all vehicles between pos+distFrom and pos+distTo
    def at(self, pos, distFrom = -CAR_LENGTH/2, distTo = CAR_LENGTH/2):
        # 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 pos+distFrom < v.pos and v.pos < pos+distTo:    # checks the␣
↪front and behind distance of the vehicles in terms of the car length defined␣
↪earlier
                res.append(v)
        # if the required distance reaches over the end of the lane segment
        if pos+distTo > self.length and self.next is not None:
            res = res + self.next.at(0, distFrom=0, distTo=distTo-(self.
↪length-pos))
        if pos+distFrom < 0 and self.prev is not None:
            res = self.prev.at(self.prev.length, distFrom=pos+distFrom,␣
↪distTo=0) + res
        return res
    def inFront(self, pos, far=FAR_AWAY_IN_FRONT):
        # 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 lance
        # 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=far-(self.length-pos))

    def behind(self, pos, far=FAR_AWAY_IN_BACK):
        # 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 lane
        if pos>far or self.prev is None:
            return None
        else:
            return self.prev.behind(self.prev.length, far=far-pos)

    def enter(self, vehicle, pos=0):     #defines the enter event for the vehicle
        self.vehicles.insert(0, vehicle)
        vehicle.pos = pos
        vehicle.lane = self
        vehicle.rec.record(vehicle, event="enter lane")

    def leave(self, vehicle):            #defines the leave lane event for the vehicle
        vehicle.rec.record(vehicle, event="leave lane")
        vehicle.lane = None
        # in the meantime the vehicle may have have moved
        # to one of the next lane segments...
        lane = self
        while lane is not None:
            if vehicle in lane.vehicles:
                lane.vehicles.remove(vehicle)
                break
            else:
                lane = lane.next
```

5.0.1 1.1 Test the construction of motorway

A single two lane 3km long motorway segment

[492]:
```
VMAX = 120/3.6   #metres/second
LANE_ID = 0
l = Lane(3000, VMAX)     # For a single long segment of 3kms to avoid crashes.␣
 ↪As advised by Christian#(See the lecture recording)
r = l.widenRight()
print("Left Lane: ", l)
print("Right Lane:", r)
```

```
Left Lane:  [0 3000m R:1]
Right Lane: [1 3000m L:0]
```

A motorway made up of little segments - A 3km two lane motorway made of 1000 m segments

[494]:
```
LANE_ID = 0
VMAX = 130/3.6
l = Lane(1000, VMAX)
while l.totalLength()<3000:
    l.extend(Lane(1000, VMAX))
r = l.widenRight()
print("Left Lane: ", l)
print("Right Lane:", r)
```

```
Left Lane:  [0 1000m R:3]-[1 1000m R:4]-[2 1000m R:5]
Right Lane: [3 1000m L:0]-[4 1000m L:1]-[5 1000m L:2]
```

A motorway made up of little segments - A 3km motorway made up of two 1500m segments

[495]:
```
LANE_ID = 0
VMAX = 130/3.6
l = Lane(1500, VMAX)
while l.totalLength()<3000:
    l.extend(Lane(1500, VMAX))
r = l.widenRight()
print("Left Lane: ", l)
print("Right Lane:", r)
```

```
Left Lane:  [0 1500m R:2]-[1 1500m R:3]
Right Lane: [2 1500m L:0]-[3 1500m L:1]
```

[ ]:

```

```

6 2. VEHICLES – defines the behaviour of vehicles

[496]:

```python
def isRunning(p):
    return p is not None and p.running

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

[803]:

```python
VEHICLE_ID = 0
# Basically, vehicle class contains properties of vehicles like position,␣
↪velocity, acceleration and rate of acceleration
class Vehicle:
    def __init__(self, env, rec,
                 startingLane=None, startingPos=0,
                 t0=0, x0=0, dx0=0, ddx0=0, dddx0=0,
                 t=[], v=[], Min_Time_Diff=1, Min_Speed_Test = 2, Car_Length =␣
↪4,
                 Far_Away_In_Front = 200, Far_Away_In_Back = 80,
                 Lane_Change_time=3, a_min=-4, a_max=2.5):

        global VEHICLE_ID   # Each vehicle is characterised by its VEHICLE_ID
        self.id = VEHICLE_ID
        VEHICLE_ID += 1


        self.Lane_Change_time = Lane_Change_time # [s]
        self.a_min = a_min # [m/s²]
        self.a_max = a_max # [m/s²] corresponds to 0-100km/h om 12s
        self.Min_Time_Diff = Min_Time_Diff
        self.Min_Speed_Test = Min_Speed_Test # [m/s] min speed diff to trigger␣
↪overtaking
        self.Car_Length = Car_Length # [m]
        self.Far_Away_In_Front = Far_Away_In_Front # [m]  distance at which a␣
↪car in front can be ignored
        self.Far_Away_In_Back = Far_Away_In_Back   # [m]  distance at which a␣
↪car behind can be ignored

        self.env = env
        self.rec = rec

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

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

        self.t0 = t0       #Initial time when the process starts
        self.x0 = x0       #Initial position of the vehicle
        self.dx0 = dx0     #Initial velocity of the vehicle
        self.ddx0 = ddx0    #Initial accelaration of the vehicle
        self.dddx0 = dddx0   # Initial rate of acceleration of the vehicle

        self.t = t     # Time profile of the vehicles (don't know how exactly␣
↪that works)
        self.v = v     #Velocty profile of the vehicles (Should be replaced␣
↪with the random speee generator funstion later)
        self.t_target = []
        self.v_target = []    #target velocity of the vehicle

        self.running = False
        self.crashed = False
        self.braking = False
        self.changingLane = False

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

        ## this allows to trigger trace messages for
        ## the new feature Surround
        self.traceSurround = False
        self.traceOvertake = False
        self.traceBrake = False

    def __str__(self):
        return f"({self.id:d})"

    #Returns true if there is no vehicle going faster than the other vehicle.␣
↪Here other vehicle refers to all the
     # other vehicle other than the point of reference vehicle
    def isNotFasterThan(self, other):
        return True if other is None else self.dx0 <= other.dx0

    #Returns true if there is no vehicle going slower than the other vehicle.␣
↪Here other vehicle refers to all the
     # other vehicle other than the point of reference vehicle
    def isNotSlowerThan(self, other):
```

```python
        return True if other is None else other.dx0 <= self.dx0

    def updateOnly(self):
        if self.crashed:
            return False
        t = self.env.now
        if t < self.t0:
            return False
        if self.running and t > self.t0:      # Euler integration for finding the position, velocity and accelaration
            dt = t - self.t0
            ddx = self.ddx0 + self.dddx0*dt
            dx = round(self.dx0 + self.ddx0*dt + self.dddx0*dt*dt/2,4)
            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  #Result of Euler integration returns time, position,
                                                                     # velocity and acceleration
            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.rec.record(self, event='end')     #Record the end event when the nextLane is none i.e when there is
                    self.running = False                   # no lane ahead
                    return False
                else:
                    nextLane.enter(self, pos=nextPos)
                    if self.oldLane is not None:
                        self.oldLane = self.oldLane.next
        return True

    def update(self):
        active = self.updateOnly()
        if not active:
            return False

        self.surround = Surround(self)   # Surround class is defined in the next cell.

        ## instead of direct link, call method
        inFront = self.surround.front
        if (isRunning(inFront) or isCrashed(inFront)) \
               and inFront.x0 < self.x0 + CAR_LENGTH:
            self.crash(inFront)
            return True

        if inFront is not None and not self.braking and \
                self.dx0 > inFront.dx0 and \
                self.x0 + CRITICAL_TIME_TOLERANCE*self.dx0 > inFront.x0:
            Δt = max(MIN_TIME_DIFF, (inFront.x0-self.x0)/self.dx0)
            self.setTarget(Δt, inFront.dx0)
            self.interruptProcess()
            return True

        ## new code: start overtaking maneuver by changing into fast lane
        if inFront is not None and \
                not self.braking and not self.changingLane and \
                self.dx0 > inFront.dx0 + MIN_SPEED_DIFF and \
                self.x0 + (LANE_CHANGE_TIME+CRITICAL_TIME_TOLERANCE)*self.dx0 > inFront.x0 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):
            if self.traceOvertake:
                print(f"t={self.t0:7,.1f}s Overtaking v{self.id:d} overtakes v{inFront.id:d} at x={self.x0:7,.1f}m")
            self.setTarget(LANE_CHANGE_TIME, 'fast')
            self.interruptProcess()
            return True

        ## new code: end overtaking by returning to slow lane
        if self.surround.leftLane is not None and \
                not self.braking and not self.changingLane and \
                self.surround.left is None and \
                self.isNotFasterThan(self.surround.leftFront) and \
                self.surround.leftBack is None:
            if self.traceOvertake:
                print(f"t={self.t0:7,.1f}s Overtaking v{self.id:d} returns to slow lane at x={self.x0:7,.1f}m")
            self.setTarget(LANE_CHANGE_TIME, 'slow')
            self.interruptProcess()
            return True

    def setTarget(self, Δt, v):
        self.t_target = [ Δt ] + self.t_target
        self.v_target = [ v ] + self.v_target

    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 = env.now
        self.running = True
        self.rec.startRecording(self)
        self.startingLane.enter(self, pos=self.startingPos)

        while self.running:
            self.updateOnly()

            self.surround = Surround(self)

            inFront = self.surround.front
            if inFront is not None:

                # if the car in front is slower and we are a bit too near on␣
↪its heals...
                if inFront.dx0 < self.dx0 and \
                        inFront.x0 < self.x0 + CRITICAL_TIME_TOLERANCE*self.dx0:
                    if self.traceBrake:
                        print(f"t={self.t0:7,.1f}s Braking v{self.id:d} v={self.
↪dx0:4.4f}m/s to {inFront.dx0:4.4f}")


                    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 = 2
                        self.setTarget(Δt, inFront.dx0)
                    continue

            if len(self.t_target)==0:
                self.t_target = self.t.copy()
                self.v_target = self.v.copy()

            if len(self.t_target)>0:

                ## add code for explicit change of lane
                if type(self.v_target[0]) is str:
                    direction = normaliseDirection(self.v_target[0])
                    t = self.t_target[0]
                    self.t_target = self.t_target[1:]
                    self.v_target = self.v_target[1:]
                    if self.lane.getLane(direction) is not None:
                        yield from self.changeLane(direction, t)

                else:
                    v0 = self.dx0
                    v1 = self.v_target[0]
                    t = self.t_target[0]
                    self.t_target = self.t_target[1:]
                    self.v_target = self.v_target[1:]
                    if isZero(v1-v0):
                        yield from self.wait(t)
                    else:
                        yield from self.adjustVelocity(v1-v0, t)
            else:
                yield from self.wait(10)

        self.rec.stopRecording(self)

    def emergencyBraking(self, v):   # defines the emergency braking procedure for vehicles

        def emergencyBrakingProcess(v):
            self.rec.record(self, 'brake')
            minΔt = 0.2
            self.dddx0 = (self.a_min-self.ddx0)/minΔt
            yield self.env.timeout(minΔt)

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


        ## The 'braking' bit prevents the interruption of an emergency breaking process
        self.braking = True
        self.processRef = self.env.process(emergencyBrakingProcess(v))
        try:
            yield self.processRef
        except simpy.Interrupt:
            pass
        self.processRef = None
        self.braking = False

    ## make changeLane robust against interrupt:
    def changeLane(self, direction, Δt):

        # smoothly adjust velocity by Δv over the time Δt
        def changeLaneProcess(oldLane, newlane, Δt):
            self.updateOnly()
            self.rec.record(self, 'change '+direction)
            self.oldLane = oldLane
            newLane.enter(self, pos=self.pos)
            self.ddx0 = 1
            self.dddx0 = 0
            yield self.env.timeout(Δt)
            currentLane = self.lane
            self.oldLane.leave(self)
            self.lane = currentLane
            self.oldLane = None
            self.rec.record(self, 'done change '+direction)
            self.updateOnly()
            self.ddx0 = 0
            self.dddx0 = 0

        ## keep record of current lane, as in case of aborting
        ## the lane change
        ## when interrupted go back into original lane
        self.updateOnly()
        oldLane = self.lane
        newLane = self.lane.getLane(direction)
        self.changingLane = True
        try:
            self.processRef = self.env.process(changeLaneProcess(oldLane,␣
↪newLane, Δt))
            yield self.processRef
            self.processRef = None
        except simpy.Interrupt:
            # if interrupted go quickly back into old lane
            # but this is not interruptible
            self.updateOnly()
            #self.lane should now be newLane. However, it is possible that self.lane is already on the next lane segment
            # in which case newlane and oldLane need to be updated in sync:
            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))
        self.changingLane = False

    def adjustVelocity(self, Δv, Δt):     # when two vehicles come closer than a certain distance, adjust velocity process is triggered

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

        self.processRef = self.env.process(adjustVelocityProcess())
        try:
            yield self.processRef
        except simpy.Interrupt:
            self.dddx0 = 0
            pass
        self.processRef = None

    def wait(self, Δt):

        def waitProcess():
            yield self.env.timeout(Δt)

        self.processRef = self.env.process(waitProcess())
        try:
            yield self.processRef
        except simpy.Interrupt:
            pass
        self.processRef = None

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

    def crash(self, other):     # function for recording the crash event

        def recordCrash(self):
            self.rec.record(self, 'crash')
            self.running = False
            self.crashed = True
            self.dx0 = 0
            self.ddx0 = 0
            self.dddx0 = 0

        if self.running:
            print(f"Crash p{self.id:d} into p{other.id:d} at t={self.t0:7.3f}␣
 ↪x={self.x0:7.1f}")
            recordCrash(self)
            if other.running:
                recordCrash(other)
```

7 3. Surround

The Surround of a vehicle is a data structure that joins a number of properties and gives access to the next vehicles to the front, back, left and right side of the vehicle.

- `leftLane` and `rightLane` are references to next `Lane` and are `None` is there is no lane to the left or right.
- `left` and `right` are Boolean values that indicate that there is a vehicle in the critical region or not.
- `front` (`leftFront`, `rightFront`) and `back` (`leftBack`, `rightBack`) are references to the `Vehicle` in the indicated region that is next to the current position. If there is no such vehicle, the references return `None`.
- The limits of the relevant regions are defined based on the current position +/- a number of car lengths +/- a distance that is a multiple of the current velocity, defined as time constants.

[804]:
```
class Surround:
    def __init__(self, vehicle):

        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}"

        # 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.leftBack = vehicle
        self.left = vehicle
        self.leftFront = vehicle
        self.back = vehicle
        self.vehicle = vehicle
        self.front = vehicle
        self.rightBack = vehicle
        self.right = vehicle
        self.rightFront = vehicle

        lane = vehicle.lane
        pos = vehicle.pos
        if lane is not None:
            self.lane = lane
            self.front = lane.inFront(pos)
            self.back = lane.behind(pos)

            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(pos)
                    self.rightBack = self.rightLane.behind(pos)
                else:
                    right = self.rightLane.at(pos)
                    if len(right)==0:
                        self.right = None
                    elif len(right)==1:
                        self.right = right[0]
                    else:
                        self.right = right

                    if self.right is None:
                        self.rightFront = self.rightLane.inFront(pos)
                        self.rightBack = self.rightLane.behind(pos)
                    else:
                        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(pos)
                    self.leftBack = self.leftLane.behind(pos)
                else:
                    left = self.leftLane.at(pos)
                    if len(left)==0:
                        self.left = None
                    elif len(left)==1:
                        self.left = left[0]
                    else:
                        self.left = left

                    if self.left is None:
                        self.leftFront = self.leftLane.inFront(pos)
                        self.leftBack = self.leftLane.behind(pos)
                    else:
                        self.leftFront = None
                        self.lefttBack = None

        if vehicle.traceSurround:
            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}|") +
                  "|"
                 )
```

8 4. Recorder

[805]:

```
class SimpleRecorder:

    def __init__(self, env, startTime, stopTime, timeStep):

        global VEHICLE_ID, LANE_ID
        VEHICLE_ID = 0
        LANE_ID = 0

        self.env = env
        self.startTime = startTime
        self.stopTime = stopTime
        self.timeStep = timeStep
        self.vehiclesToTrace = []
        self.vehicles = []
        self.data = pd.DataFrame(columns=['t', 'x', 'v', 'a', 'id', 'lane',␣
↪'oldLane', 'pos', 'event'])

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

    def startRecording(self, p):
        self.vehicles.append(p)

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

    def record(self, p=None, event='timer'):
        if p is not None:
            if p.updateOnly():
                laneId = None if p.lane is None else p.lane.id
                oldLaneId = None if p.oldLane is None else p.oldLane.id
                if p.running or event!='timer':
                    ix = len(self.data)
                    self.data.loc[ix]=[self.env.now, p.x0, p.dx0, p.ddx0, p.id,␣
↪laneId, oldLaneId, p.pos, event]
                    if event=='timer':
                        p.update()
        else:
            for p in self.vehicles:
                self.record(p)

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

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

    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 plot(self, x, y,
             vehicles=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=(6, 4), 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, '', data=df)
            plt.xlabel(labels[xindex])
            plt.ylabel(labels[yindex])

            # use small circle to indicate emergency braking
            db = df[df.event=='brake']
            for i in range(len(db)):
                X = db.iloc[i, xindex]
                Y = db.iloc[i, yindex]
                plt.plot([X], [Y], 'ro')
            # 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 right pointing triangle
            # to indicate that a vehicle
            # was 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 left pointing triangle
            # to indicate that a vehicle
            # was 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], '<k')

            # 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')

        plt.grid(True)
```

[ ]:

```

```

9 5. Verification of the classes and functions

5.1- Controlled Change of Lane – for a 500m motorway. The ‘R’ in the list of v indicates the vehicle has to turn right

[806]:

```
VMAX = 120/3.6     # m/s
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 10, 0.5)
l = Lane(500, VMAX)
r = Lane(500, VMAX)
```

```
l.attachRight(r)
v = Vehicle(env, rec, startingLane=l, dx0=20, t=[2, 2, 2, 2, 10], v=[20, 'R',␣
 ↪20, 20, 20])  # 'R' in the argument means the vehicle has to turn right
v.traceSurround=True
rec.run()
```

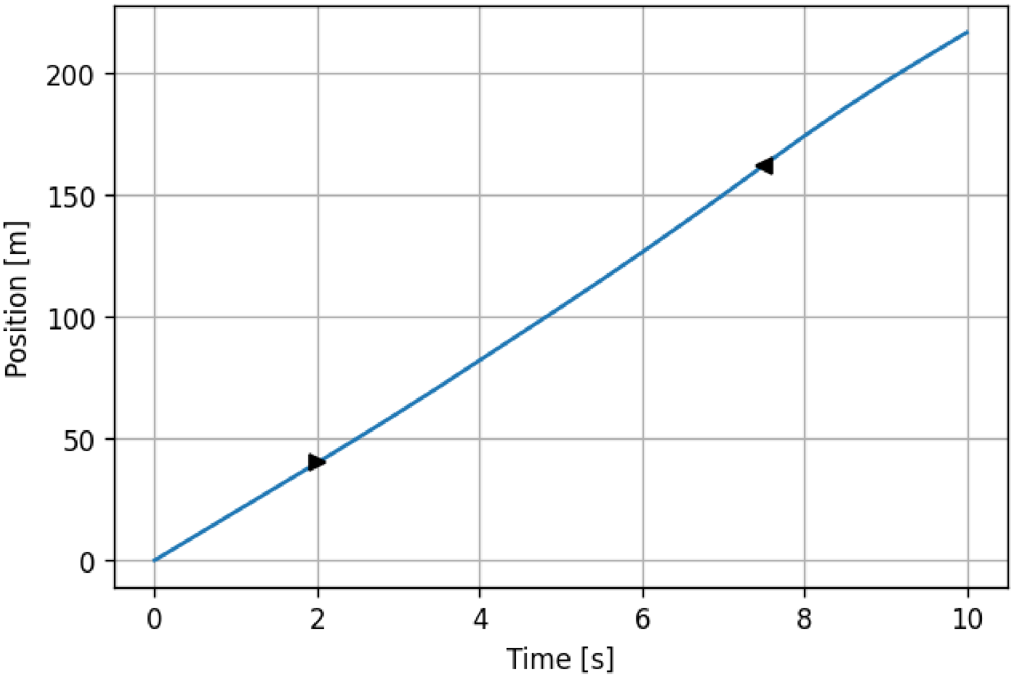
```
surround t=  0.00 || >0> | > > ||
surround t=  0.00 || >0> | > > ||
surround t=  0.50 || >0> | > > ||
surround t=  1.00 || >0> | > > ||
surround t=  1.50 || >0> | > > ||
surround t=  2.00 || >0> | > > ||
surround t=  2.00 || >0> | > > ||
surround t=  2.50 || >0> | >0> ||
surround t=  3.00 || >0> | >0> ||
surround t=  3.50 || >0> | >0> ||
surround t=  4.00 || > > | >0> ||
surround t=  4.00 || > > | >0> ||
surround t=  4.50 || > > | >0> ||
surround t=  4.50 || > > | >0> ||
surround t=  5.00 || >0> | >0> ||
surround t=  5.50 || >0> | >0> ||
surround t=  6.00 || >0> | >0> ||
surround t=  6.50 || >0> | >0> ||
surround t=  7.00 || >0> | >0> ||
surround t=  7.50 || >0> | > > ||
surround t=  7.50 || >0> | > > ||
surround t=  8.00 || >0> | > > ||
surround t=  8.50 || >0> | > > ||
surround t=  9.00 || >0> | > > ||
surround t=  9.50 || >0> | > > ||
surround t=  9.50 || >0> | > > ||
surround t= 10.00 || >0> | > > ||
```

[807]:
```
rec.getData().head(10)
```

[807]:
```
     t      x     v    a  id  lane oldLane    pos        event
0    0      0    20    0   0     0    None      0   enter lane
1    0      0    20    0   0     0    None      0        timer
2  0.5   10.0  20.0  0.0   0     0    None   10.0        timer
3  1.0   20.0  20.0  0.0   0     0    None   20.0        timer
4  1.5   30.0  20.0  0.0   0     0    None   30.0        timer
5  2.0   40.0  20.0  0.0   0     0    None   40.0        timer
6    2   40.0  20.0  0.0   0     0    None   40.0  change fast
7    2   40.0  20.0  0.0   0     1       0   40.0   enter lane
8  2.5  50.12  20.5  1.0   0     1       0  50.12        timer
9  3.0  60.49  21.0  1.0   0     1       0  60.49        timer
```

[762]:

```
rec.plot('t','x')
```



5.2- Multiple Vehicles with fixed speed profile

[808]:

```
VMAX = 20  # No need for conversion. Already in m/s
N = 50   # No. of vehicles
DT = 18 # time difference between start. DT is a constant and all the vehicles␣
 ↪will have this constant difference in their arrival time
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1000, 1)   # The simulation will run for 1000␣
 ↪seconds

l = Lane(3000, VMAX)
l.extend(Lane(3000, VMAX))
r = l.widenRight()
for i in range(N):
    v = Vehicle(env, rec, startingLane=l, t0=i*DT, dx0=VMAX+3*i, t=[10],␣
 ↪v=[VMAX+3*i])
    v.traceOvertake = True   # for tracing the overtaking events
    v.traceSurround - True
rec.run()
```

```
t=   85.0s Overtaking v1 overtakes v0 at x=1,541.0m
t=  142.0s Overtaking v3 overtakes v2 at x=2,552.0m
t=  149.0s Overtaking v2 overtakes v0 at x=2,888.1m
```

```
t=  159.0s Overtaking v1 returns to slow lane at x=3,262.5m
t=  190.0s Overtaking v5 overtakes v4 at x=3,500.0m
t=  191.0s Overtaking v4 overtakes v0 at x=3,720.9m
t=  230.0s Overtaking v6 overtakes v0 at x=4,499.4m
t=  233.0s Overtaking v2 returns to slow lane at x=5,064.3m
t=  234.0s Overtaking v5 returns to slow lane at x=4,763.0m
t=  253.0s Overtaking v8 overtakes v7 at x=4,796.0m
t=  267.0s Overtaking v8 returns to slow lane at x=5,431.5m
t=  269.0s Overtaking v3 returns to slow lane at x=5,969.9m
```

[809]:

```
rec.getData().head()
```

[809]:

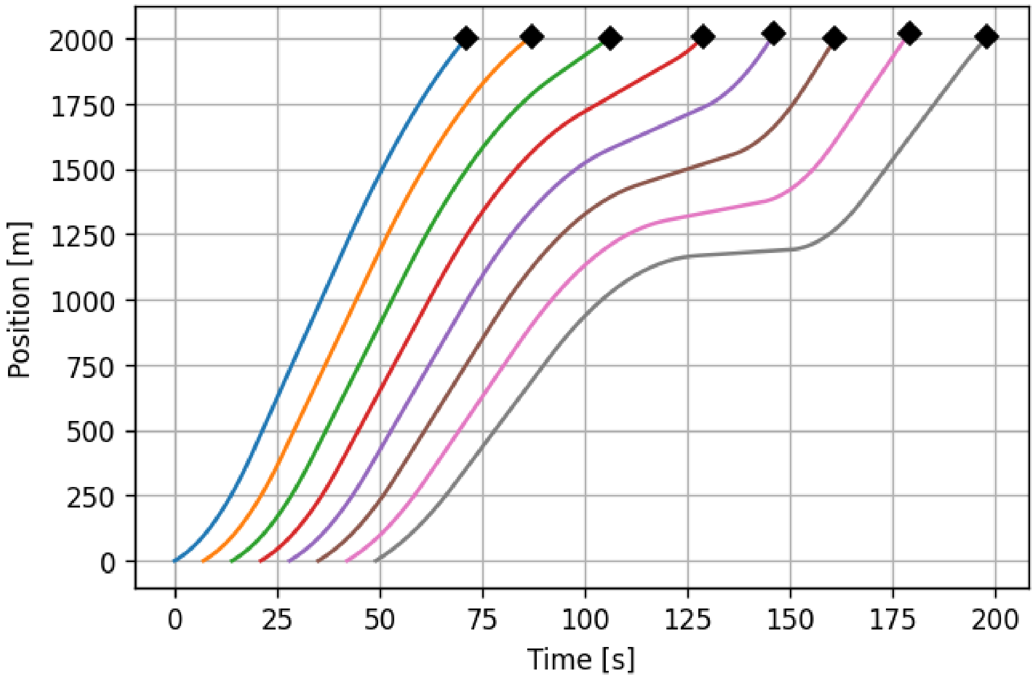
```
   t     x     v  a id lane oldLane   pos       event
0  0     0    20  0  0    0    None     0  enter lane
1  0     0    20  0  0    0    None     0       timer
2  1  20.0  20.0  0  0    0    None  20.0       timer
3  2  40.0  20.0  0  0    0    None  40.0       timer
4  3  60.0  20.0  0  0    0    None  60.0       timer
```

[810]:

```
VMAX = 30
N = 8
DT = 7 # time difference between start
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 200, 1)
l = Lane(1000, VMAX)
l.extend(Lane(1000, VMAX))
r = l.widenRight()
for i in range(N):
    v = Vehicle(env, rec, startingLane=l, t0=i*DT, dx0=10, t=[20, 20, 40, 20],␣
 ↪v=[35-2*i, 35-2*i, 15-2*i, 15-2*i])
    v.traceOvertake = True
#     v.traceSurround = True
rec.run()
```

[811]:

```
rec.plot('t', 'x')
```



[767]:

```
rec.getEvents().head()
```

[767]:

```
     t  x   v  a id lane oldLane pos      event
0    0  0  10  0  0    0    None   0 enter lane
8    7  0  10  0  1    0    None   0 enter lane
23  14  0  10  0  2    0    None   0 enter lane
45  21  0  10  0  3    0    None   0 enter lane
74  28  0  10  0  4    0    None   0 enter lane
```

5.3- Testing Vehicles with random speed profiles

[768]:

```
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) ]
```

[769]:

```
times = randomIntervals(10)
times
```

[769]:

```
[76.9791151964325,
 71.73641684827929,
 115.02616521972475,
 95.61894094409733,
 41.399548572980024,
 107.15760533818501,
 56.56954716295382,
 98.49940463205168,
 83.60917956507673,
 131.4190607387929]
```

[770]:

```
SPEED_VARIATION = 0.05
def randomSpeedVariation(vmax, cycles, cv=SPEED_VARIATION):
    return [ vmax + (-1)**i*abs(random.normalvariate(0, vmax*cv)) for i in␣
 ↪range(cycles) ]
```

[771]:

```
speed = randomSpeedVariation(30,10)
speed
```

[771]:

```
[30.185305492901904,
 28.769778415001056,
 31.682565594115577,
 29.782063127423445,
 30.359585607708997,
 28.82880460076298,
 31.747700062402206,
 27.402952053582357,
 30.375841491412128,
 28.651287134238228]
```

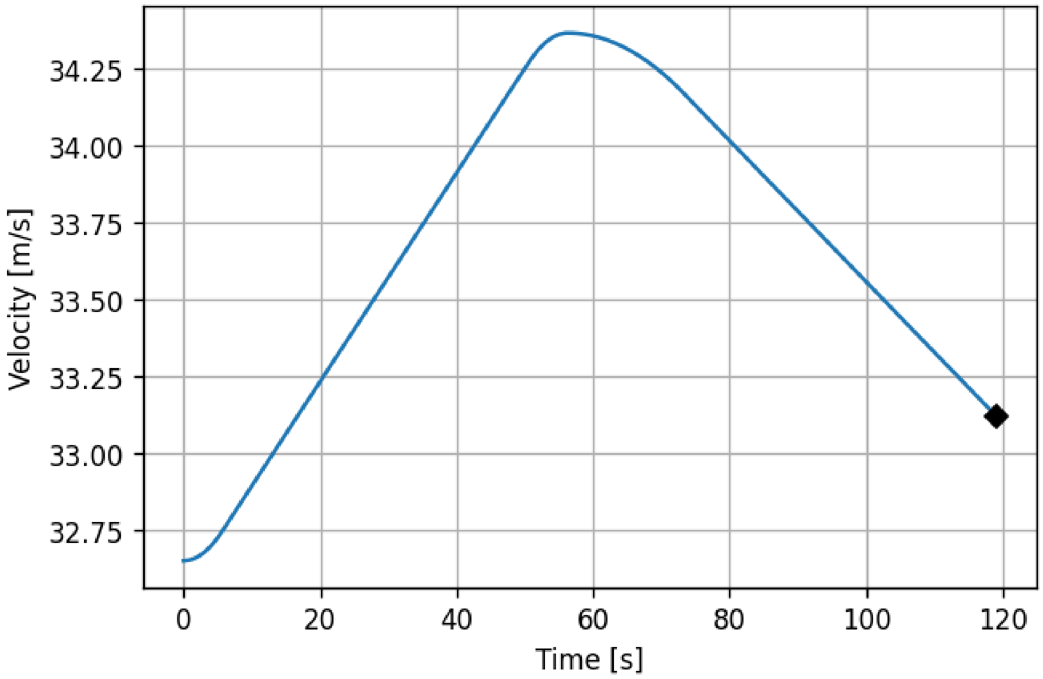
5.3.1- Single vehicle of varying speed

[772]:

```
CYCLES = 6
VMAX = 120/3.6     #m/s
random.seed(13)
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1000, 1)

#testing on a 4km motorway made of four 1kms segments
l = Lane(4000, VMAX)
while l.totalLength()<4000:
    l.extend(Lane(1000, VMAX))
r = l.widenRight()

times = randomIntervals(CYCLES)
speed = randomSpeedVariation(VMAX, CYCLES)
Vehicle(env, rec, startingLane=l, dx0=speed[-1], t=times, v=speed)
rec.traceOvertake = True
rec.run()
```

[773]:

```
rec.plot('t','v')
```



[774]:

```
rec.getData().head()
```

[774]:

```
   t      x          v         a  id lane oldLane    pos       event
0  0      0  32.652364         0   0    0    None      0  enter lane
1  0      0  32.652364         0   0    0    None      0       timer
2  1  32.65  32.655400  0.006026   0    0    None  32.65       timer
3  2  65.31  32.664400  0.012052   0    0    None  65.31       timer
4  3  97.98  32.679500  0.018078   0    0    None  97.98       timer
```

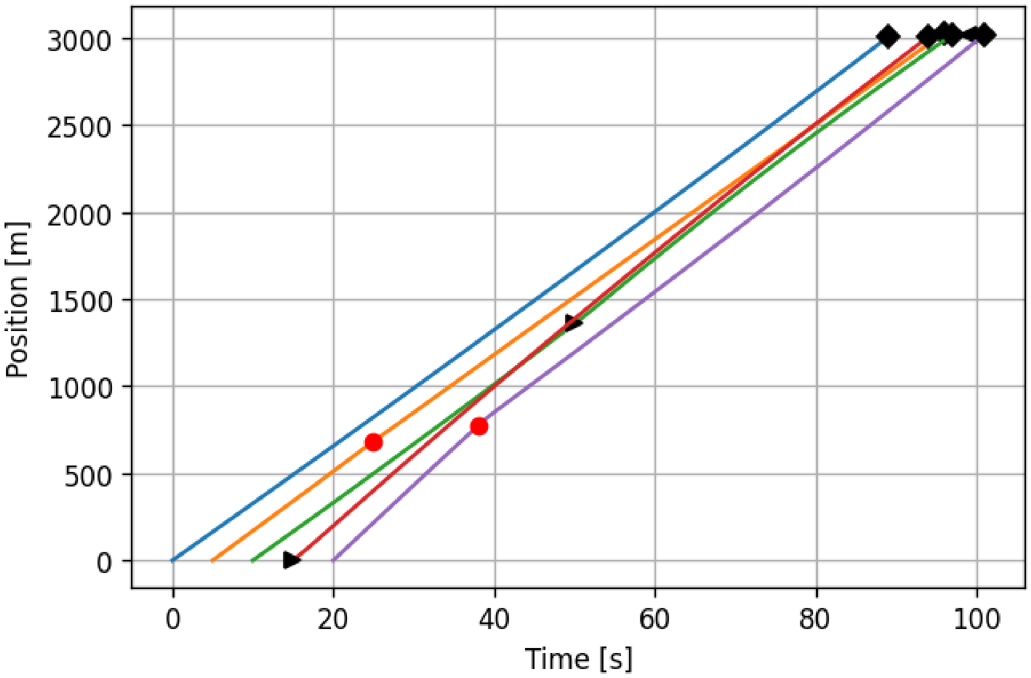
5.3.2- Multiple vehicles with varying speed

[775]:

```
#Multiple Vehicles with varying speed
VMAX = 120/3.6
N = 5 # number of points
DT = 5 # time difference between start
random.seed(13)
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 4000, 1)

l = Lane(3000, VMAX)
while l.totalLength()<3000:
    l.extend(Lane(1000, VMAX))
r = l.widenRight()

print('l', l)
print('r', r)
for i in range(N):
    CYCLES = random.randint(4, 8)
    times = randomIntervals(CYCLES)
    speed = randomSpeedVariation(VMAX+i, CYCLES)
    v = Vehicle(env, rec, startingLane=l, t0=i*DT, dx0=speed[-1], t=times,␣
 ↪v=speed)
    v.traceOvertake = True

rec.run()
```

```
l [0 3000m R:1]
r [1 3000m L:0]
t=   15.0s Overtaking v3 overtakes v2 at x=    0.0m
t=   50.0s Overtaking v2 overtakes v1 at x=1,359.2m
t=   96.0s Overtaking v2 returns to slow lane at x=2,987.2m
```

[776]:
```
rec.plot('t', 'x')
```



5.4- Multiple vehicles with fixed speed

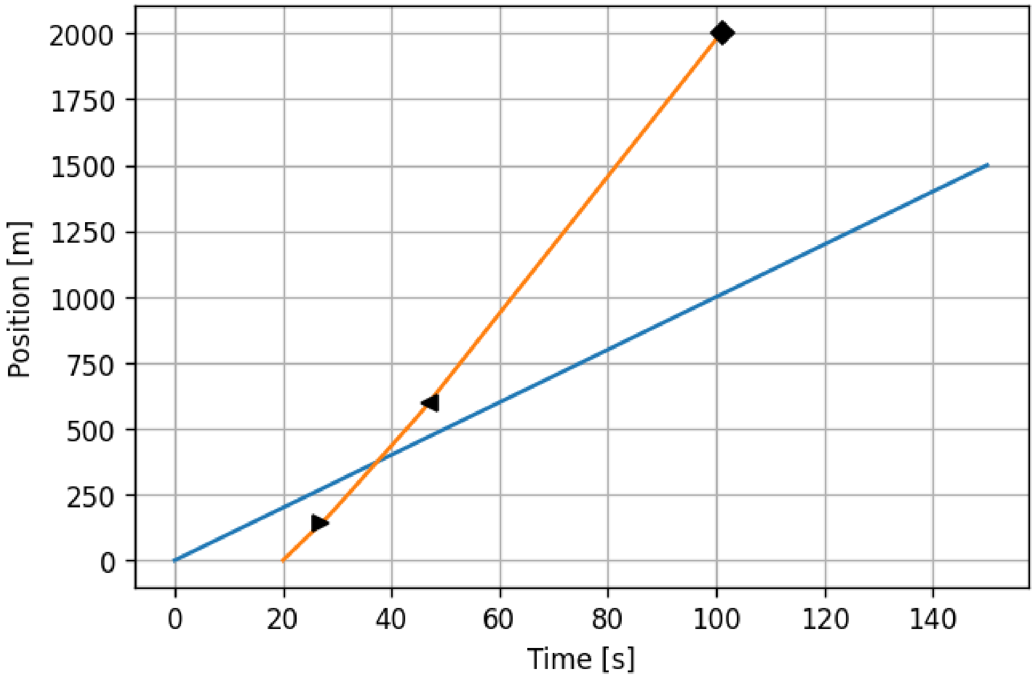
[777]:
```
#Two vehicles with not enough distance between them
VMAX = 120/3.6      #m/s
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 150, 1)
```

```
l = Lane(2000, VMAX)
r = l.widenRight()
Vehicle(env, rec, startingLane = l, t0=0, dx0=10)
Vehicle(env, rec, startingLane = l, t0=20, dx0=20)
rec.run()
# rec.traceSurround = True
```

[778]:
```
rec.getData().head()
```

[778]:
```
   t     x     v  a id lane oldLane   pos       event
0  0     0    10  0  0    0    None     0  enter lane
1  0     0    10  0  0    0    None     0       timer
2  1  10.0  10.0  0  0    0    None  10.0       timer
3  2  20.0  10.0  0  0    0    None  20.0       timer
4  3  30.0  10.0  0  0    0    None  30.0       timer
```

[779]:
```
rec.plot('t','x')
```

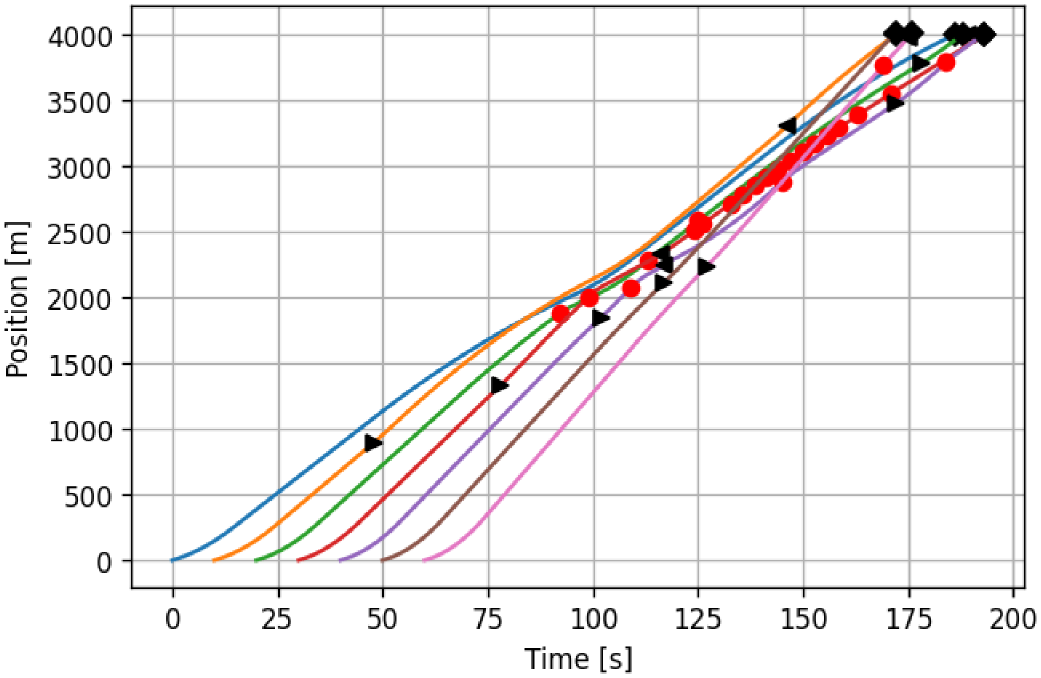


[780]:
```
# A large number of vehicles with not enough distance between them
VMAX = 120/3.6
N = 7
DT = 10 # time difference between start
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1000, 1)
```

```
l = Lane(4000, VMAX)
r = l.widenRight()
for i in range(N):
    Vehicle(env, rec, startingLane=l, t0=i*DT, dx0=10, t=[15, 30, 50],␣
 ↪v=[25+2*i, 25+2*i, 15+2*i])
rec.run()
```

[781]:

```
rec.plot('t', 'x')
```



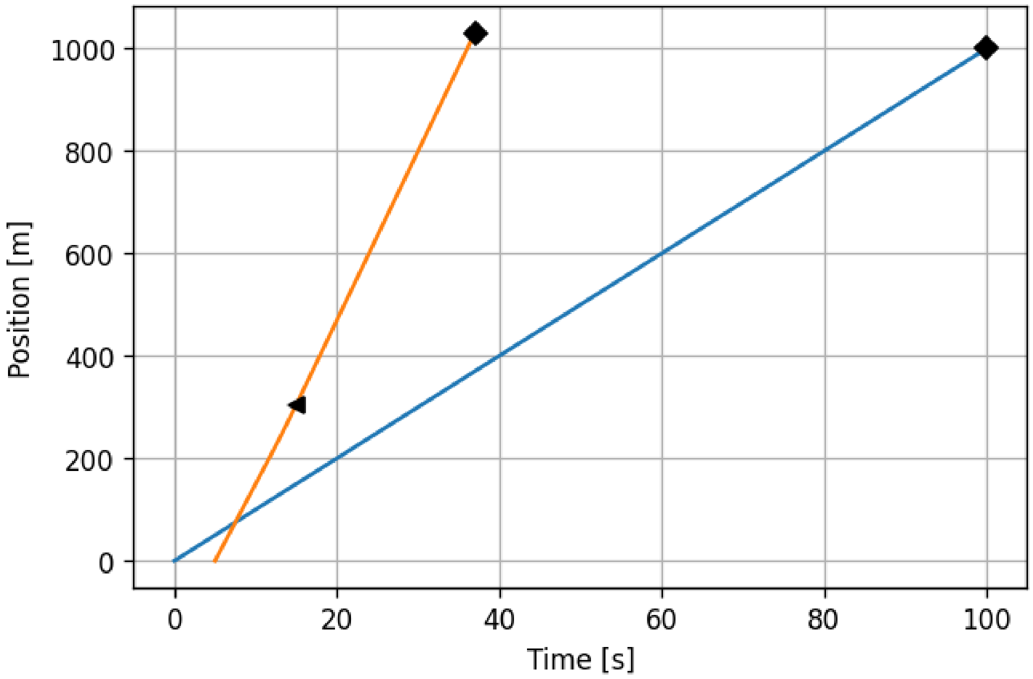
5.5- Crash Scenario

[782]:

```
#Crash scenario  -- only two vehicles
VMAX = 120/3.6
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 150, 1)
l = Lane(1000, VMAX)
r = l.widenRight()
Vehicle(env, rec, startingLane=l, t0=0, dx0=10)
Vehicle(env, rec, startingLane=r, t0=5, dx0=30)
rec.run()
```

[783]:

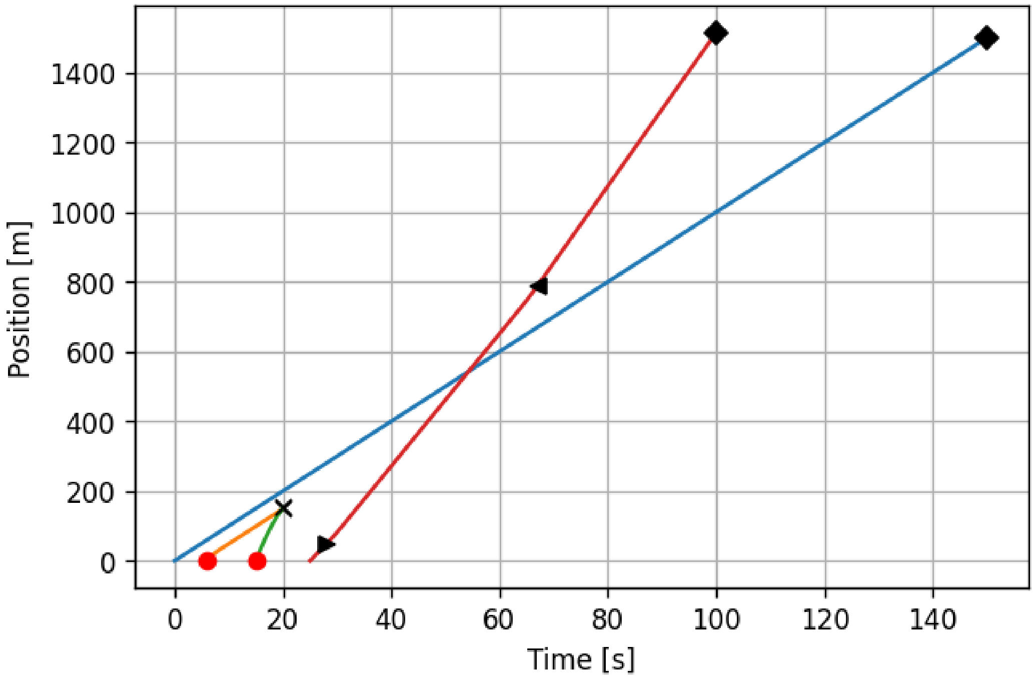
```
rec.plot('t','x')
```



[784]:
```
# Crash scenario -- multiple vehicles
VMAX = 120/3.6
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 150, 1)
l = Lane(1500, VMAX)
r = l.widenRight()
Vehicle(env, rec, startingLane=l, t0=0, dx0=10)
Vehicle(env, rec, startingLane=l, t0=6, dx0=18)
Vehicle(env, rec, startingLane=l, t0=15, dx0=40)
Vehicle(env, rec, startingLane=l, t0=25, dx0=16)
rec.run()
```

```
Crash p1 into p2 at t= 20.000 x=  148.8
```

[785]:
```
rec.plot('t','x')
```



[786]:

```
rec.getData().head()
```

[786]:

```
   t     x     v  a id lane oldLane   pos       event
0  0     0    10  0  0    0    None     0  enter lane
1  0     0    10  0  0    0    None     0       timer
2  1  10.0  10.0  0  0    0    None  10.0       timer
3  2  20.0  10.0  0  0    0    None  20.0       timer
4  3  30.0  10.0  0  0    0    None  30.0       timer
```

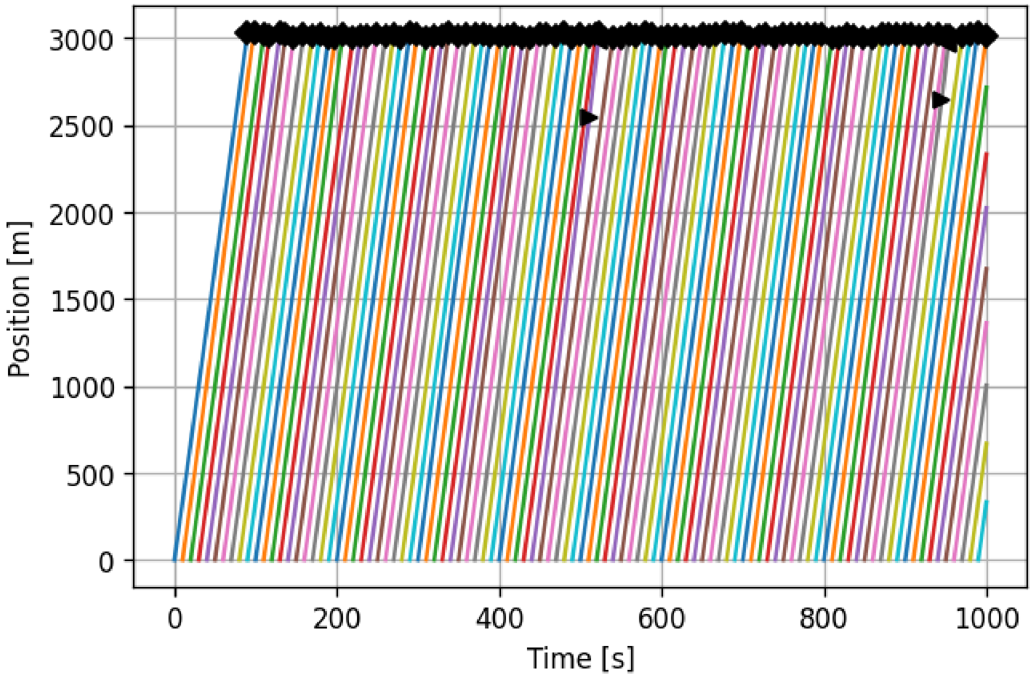
5.6- Row of vehicles with varying speed (Random speeds)

[789]:

```
VMAX = 120/3.6   # m/s
N = 100 # number of vehicles
DT = 10 # time difference between start
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1000, 1)
l = Lane(3000, VMAX)                ### Row of Cars with Varying Speed
r = l.widenRight()
for i in range(N):
    CYCLES = random.randint(4, 8)
    times = randomIntervals(CYCLES)
    speed = randomSpeedVariation(VMAX, CYCLES)
    Vehicle(env, rec, startingLane=l, t0=i*DT, dx0=VMAX, t=times, v=speed)
    rec.traceOvertake = True
    rec.traceSurround = True
rec.run()
```

[790]:

```
rec.plot('t','x')
```



CA tasks start here………

10 CA Task 1: Simulation of a two lane motorway and calculation of throughput, average travelling time, average speed and traffic density

Details: The first task involves simulating a two lane motorway and then calculating the below mentioned quantities. For accomplishing this task, we have used the code provided in the class and added the following components to it: * **chooseLane() method**: This function allows a vehicle to choose between the two lanes at random but with specific weights given to each lane. For the **left/slow lane**, we have given a weight of **0.80** since majority of the vehicles will be starting from this lane only. The **right/fast lane** is given a weight of **0.20** since only a small fraction of incoming vehicles pass through this lane. * We have used **different inter-arrival times** for each of the two lanes **IAT_fast** and **IAT_slow**. We ran different simulations with different values for the two inter-arrival times. * A condition is added to the main simulation loop allowing vehicles starting from the left lane to use IAT_fast and those starting from the right lane to use *IAT_slow*. * For calculating the *iat*, a **uniform distribution** has been used instead of an expovariate distribution to reduce the variation. Moreover, expovariate distribution generated a few extremely small values like 0.0048 for the inter-arrival time which caused crashes.

The following four quantities have been computed from the simulation dataframe. * **Throughput**: Cumulative volume across all the lanes going in one direction measured and averaged over a prolonged period of time. * **Average Travelling time**: Average time taken by a vehicle to cross the entire motorway. * **Average Speed**: $\frac{\text{Length of the motorway}}{\text{Average travelling time}}$ * **Traffic density**: $\frac{\text{Throughput}}{\text{Average speed}}$

11 CA Task 2: Simulation of a two lane motorway incorporating the human driving behaviour.

Details: The second task is an extension of the first task to simulate the human driving behaviour. In this task, we will be using the **freeMotorwaySpeed()** function from the trafffic data generation file for generating the speed of the vehicles.Another aspect introduced to capture the real world scenario is the use of **chooseVehicle()** method which randomly generates a vehicle type between electrical and diesel for the simulation. The minimum and maximum accelerations will be decided for the vehicle based on the choice generated(electrical or diesel)

12 Task-1

12.0.1 Defining the function for the choosing of the lanes

Since we have to choose the different inter-arrival times for each lane, we can also define a function that enables a vehicle to choose a specific lane based on the weights given in the random function. Here, I take the assumption that 80% of the vehicles that enter the simulation will take the slow lane (left) and the rest 20% will take the fast lane (right).

[585]:
```
def chooseLane(laneList):
    lane = random.choices(laneList, [0.80, 0.20])[0]

    return lane
```

[586]:
```
#Checking if the function works correctly
choice = [chooseLane(['l', 'r']) for i in range(50)]
print(choice)
```

```
['l', 'l', 'l', 'l', 'l', 'r', 'l', 'r', 'l', 'r', 'l', 'r', 'l', 'r', 'r', 'l',
'l', 'l', 'l', 'l', 'l', 'l', 'l', 'l', 'r', 'l', 'l', 'l', 'r', 'l', 'r', 'r',
'l', 'r', 'l', 'l', 'l', 'l', 'l', 'r', 'l', 'r', 'l', 'r', 'l', 'l', 'l', 'l',
'r', 'l']
```

Checking the ranges of the distributions used for calculating inter-arrival time

[587]:
```
#Expovariate distribution
IAT = 18
iat_e = [ random.expovariate(1.0/IAT) for i in range(3000) ]
print(max(iat_e), min(iat_e))
```

```
140.2108409657023 0.01015514620349752
```

[588]:
```
#Normal distribution
IAT = 20
iat_u = [random.uniform(IAT/10, IAT+10) for i in range(3000)]
print(max(iat_u), min(iat_u))
```

```
29.999528057788982 2.0068813787684783
```

Defining the function for choosing IATs based on lanes

[589]:
```
# IAT_slow = 13  #Average interarrival time for the slow lane
# IAT_fast = 10   #Average interarrival time for the fast lane
def chooseIAT(choice):
    if choice == 'l':
        IAT = IAT_slow
    else:
        IAT = IAT_fast
    return IAT
```

[590]:
```
IAT_slow = 13  #Average interarrival time for the slow lane
IAT_fast = 10   #Average interarrival time for the fast lane
IAT_final = [chooseIAT(choice[i]) for i in range(10)]
IAT_final # Funciton Works
```

[590]:
```
[13, 13, 13, 13, 13, 10, 13, 10, 13, 10]
```

[581]:
```
chooseIAT('l')
```

[581]:
```
13
```

[591]:
```
chooseIAT('r')
```

[591]:
```
10
```

Running the simulation using above functions

1. Using single inter-arrival time value for both lanes with uniform distribution

[740]:
```
VMAX = 120/3.6
N = 3000 # number of points
IAT =  5# average interarrival time
random.seed(13)
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1800, 1)
#iat = [ random.expovariate(1.0/IAT) for i in range(N) ]
iat = [random.uniform(IAT/10, IAT+10) for i in range(N)]
l = Lane(3000, VMAX)
r = l.widenRight()

t0 = 0
for i in range(N):
    CYCLES = random.randint(4, 8)
    times = randomIntervals(CYCLES)
    speed = randomSpeedVariation(VMAX, CYCLES)
    t0 += iat[i]
    v = Vehicle(env, rec, startingLane=1, t0=t0, dx0=speed[-1], t=times,␣
 ↪v=speed)
    v.traceOvertake = True
rec.run()
```

```
t=  131.0s Overtaking v8 overtakes v7 at x=2,281.8m
t=  139.0s Overtaking v10 overtakes v9 at x=2,252.1m
t=  148.0s Overtaking v8 returns to slow lane at x=2,908.8m
t=  156.0s Overtaking v10 returns to slow lane at x=2,897.6m
t=  200.0s Overtaking v19 overtakes v18 at x=2,307.3m
t=  216.0s Overtaking v19 returns to slow lane at x=2,905.1m
t=  246.0s Overtaking v25 overtakes v24 at x=1,398.5m
t=  248.0s Overtaking v28 overtakes v27 at x=  645.8m
t=  270.0s Overtaking v33 overtakes v32 at x=   14.0m
t=  290.0s Overtaking v25 returns to slow lane at x=2,979.8m
t=  397.0s Overtaking v49 overtakes v48 at x=  168.1m
t=  435.0s Overtaking v57 overtakes v56 at x=   12.8m
t=  444.0s Overtaking v47 overtakes v46 at x=2,106.9m
t=  445.0s Overtaking v49 returns to slow lane at x=1,888.8m
t=  465.0s Overtaking v58 overtakes v56 at x=  941.5m
t=  467.0s Overtaking v47 returns to slow lane at x=2,966.0m
t=  509.0s Overtaking v58 returns to slow lane at x=2,408.1m
t=  601.0s Overtaking v76 overtakes v75 at x=   33.0m
t=  611.0s Overtaking v70 overtakes v69 at x=2,409.1m
t=  626.0s Overtaking v70 returns to slow lane at x=2,955.9m
t=  656.0s Overtaking v76 returns to slow lane at x=2,008.7m
t=  702.0s Overtaking v83 overtakes v82 at x=1,407.6m
t=  744.0s Overtaking v83 returns to slow lane at x=2,937.9m
t=  755.0s Overtaking v87 overtakes v86 at x=2,006.1m
t=  767.0s Overtaking v95 overtakes v94 at x=  989.8m
t=  781.0s Overtaking v87 returns to slow lane at x=2,962.2m
t=  782.0s Overtaking v91 overtakes v90 at x=2,114.8m
t=  803.0s Overtaking v92 overtakes v90 at x=2,771.0m
t=  805.0s Overtaking v91 returns to slow lane at x=2,961.8m
t=  822.0s Overtaking v105 overtakes v104 at x=1,016.4m
t=  825.0s Overtaking v99 overtakes v98 at x=2,166.4m
t=  837.0s Overtaking v97 overtakes v92 at x=2,809.6m
t=  839.0s Overtaking v113 overtakes v112 at x=   19.8m
t=  853.0s Overtaking v101 overtakes v100 at x=2,768.1m
t=  856.0s Overtaking v102 overtakes v97 at x=2,825.5m
t=  880.0s Overtaking v106 overtakes v97 at x=2,809.3m
t=  893.0s Overtaking v113 returns to slow lane at x=2,071.8m
t=  902.0s Overtaking v114 overtakes v112 at x=2,012.0m
t=  920.0s Overtaking v121 overtakes v120 at x=  697.9m
```

```
t=  976.0s Overtaking v125 overtakes v124 at x=1,290.0m
t=  978.0s Overtaking v128 overtakes v127 at x=  425.2m
t=  980.0s Overtaking v120 overtakes v119 at x=2,786.3m
t=  980.0s Overtaking v131 overtakes v130 at x=    5.6m
t=  998.0s Overtaking v135 overtakes v134 at x=   61.9m
t=1,006.0s Overtaking v125 returns to slow lane at x=2,377.8m
t=1,036.0s Overtaking v136 overtakes v134 at x=1,310.0m
t=1,056.0s Overtaking v144 overtakes v143 at x=   16.4m
t=1,065.0s Overtaking v132 overtakes v130 at x=2,788.6m
t=1,073.0s Overtaking v134 overtakes v133 at x=2,748.6m
t=1,076.0s Overtaking v146 overtakes v145 at x=  322.1m
t=1,106.0s Overtaking v152 overtakes v151 at x=   10.9m
t=1,112.0s Overtaking v144 returns to slow lane at x=2,047.7m
t=1,121.0s Overtaking v156 overtakes v155 at x=    4.1m
t=1,124.0s Overtaking v142 overtakes v141 at x=2,750.9m
t=1,145.0s Overtaking v145 overtakes v120 at x=2,831.2m
t=1,150.0s Overtaking v153 overtakes v151 at x=1,361.5m
t=1,184.0s Overtaking v156 returns to slow lane at x=2,303.1m
t=1,188.0s Overtaking v156 overtakes v154 at x=2,450.2m
t=1,192.0s Overtaking v153 returns to slow lane at x=2,868.3m
t=1,231.0s Overtaking v161 overtakes v160 at x=2,159.1m
t=1,243.0s Overtaking v173 overtakes v172 at x=    4.2m
t=1,252.0s Overtaking v172 overtakes v171 at x=  498.3m
t=1,255.0s Overtaking v173 returns to slow lane at x=  470.7m
t=1,269.0s Overtaking v164 overtakes v163 at x=2,767.6m
t=1,288.0s Overtaking v166 overtakes v165 at x=2,746.0m
t=1,319.0s Overtaking v173 overtakes v171 at x=2,679.0m
t=1,346.0s Overtaking v176 overtakes v175 at x=2,737.9m
t=1,351.0s Overtaking v183 overtakes v182 at x=  523.2m
t=1,368.0s Overtaking v178 overtakes v177 at x=2,725.4m
t=1,411.0s Overtaking v192 overtakes v191 at x=    7.1m
t=1,457.0s Overtaking v187 overtakes v186 at x=2,760.0m
t=1,465.0s Overtaking v189 overtakes v188 at x=2,711.8m
t=1,478.0s Overtaking v198 overtakes v197 at x=1,071.3m
t=1,515.0s Overtaking v194 overtakes v193 at x=2,754.3m
t=1,576.0s Overtaking v203 overtakes v202 at x=2,738.5m
t=1,618.0s Overtaking v220 overtakes v219 at x=    5.4m
t=1,692.0s Overtaking v216 overtakes v120 at x=2,812.8m
t=1,697.0s Overtaking v219 overtakes v218 at x=2,627.6m
t=1,729.0s Overtaking v230 overtakes v229 at x=  539.5m
t=1,747.0s Overtaking v234 overtakes v233 at x=   80.5m
t=1,760.0s Overtaking v226 overtakes v225 at x=2,793.1m
t=1,780.0s Overtaking v230 returns to slow lane at x=2,368.3m
t=1,790.0s Overtaking v229 overtakes v228 at x=2,758.8m
```

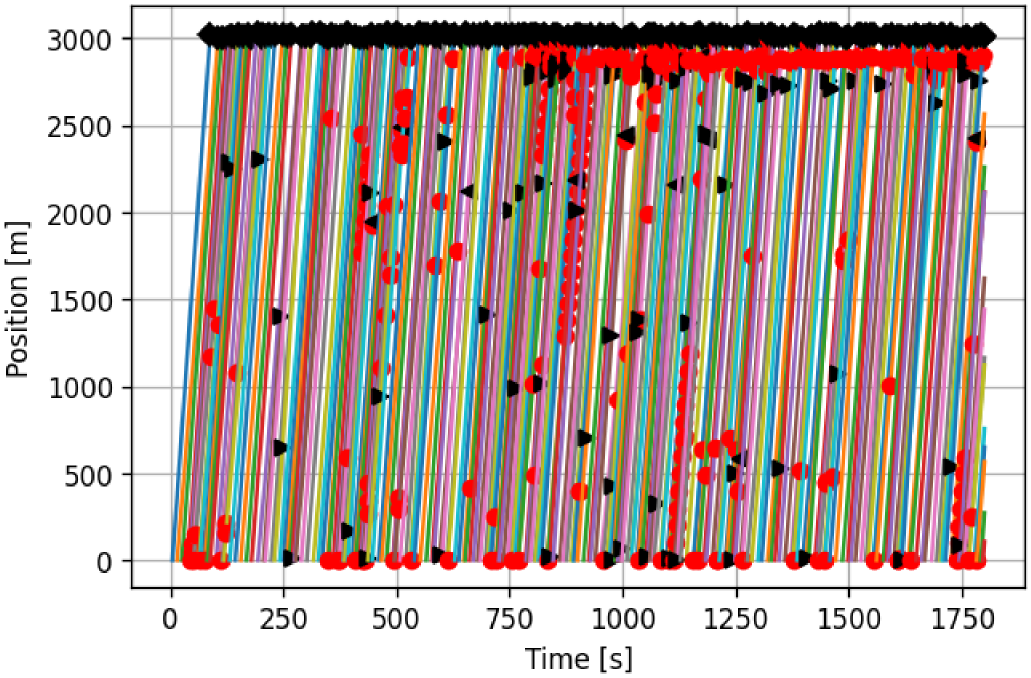
```
[741]: rec.getData()
```

[741]:

```
                 t       x          v         a   id lane oldLane     pos  \
0         4.255623       0  35.557611         0    0    0    None       0
1         5.000000   26.47  35.558300  0.001977    0    0    None   26.47
2         6.000000   62.03  35.561600  0.004632    0    0    None   62.03
3         7.000000   97.59  35.567600  0.007288    0    0    None   97.59
4         8.000000  133.16  35.576200  0.009944    0    0    None  133.16
…            …     …        …       …  …  …     …     …
22667  1800.000000  756.82  34.243300  0.028964  239    0    None  756.82
22668  1800.000000  648.71  33.928400   0.01331  240    0    None  648.71
22669  1800.000000  565.48  32.950300  0.010764  241    0    None  565.48
22670  1800.000000  273.69  33.589300  0.023273  242    0    None  273.69
22671  1800.000000   108.0  33.618300   0.00338  243    0    None   108.0

            event
0      enter lane
1           timer
2           timer
3           timer
4           timer
…           …
22667       timer
22668       timer
22669       timer
22670       timer
22671       timer

[22672 rows x 9 columns]
```

[742]:

```
rec.plot('t','x')
```



12.0.2 Average Travelling Time and Speeds

Method- 1

```
[743]: df = rec.getData()
```

```
[744]: enter_lane_df = rec.getData().loc[rec.getData().event == 'enter lane']
       enter_lane_df = enter_lane_df.groupby(['id', 'event'])['t']
       # enter_lane_df.describe()
       end_df = rec.getData().loc[rec.getData().event == 'end']
       end_df = end_df.groupby(['id', 'event'])['t']
       # end_df.describe()
       time_diff_df = pd.merge(left = enter_lane_df.describe(), right = end_df.
        ↪describe(), on = 'id', how = 'inner', suffixes = ('_enter_lane',␣
        ↪'_end_lane'))
       time_diff_df.head()
```

```
[744]:     count_enter_lane  mean_enter_lane  std_enter_lane  min_enter_lane  \
       id
       0                1.0         4.255623             NaN        4.255623
       1                1.0        14.691864             NaN       14.691864
       2                1.0        25.111052             NaN       25.111052
       3                1.0        37.926426             NaN       37.926426
       4                1.0        41.119427             NaN       41.119427
```

```
    25%_enter_lane  50%_enter_lane  75%_enter_lane  max_enter_lane  \
id
0         4.255623        4.255623        4.255623        4.255623
1        14.691864       14.691864       14.691864       14.691864
2        25.111052       25.111052       25.111052       25.111052
3        37.926426       37.926426       37.926426       37.926426
4        41.119427       41.119427       41.119427       41.119427

    count_end_lane  mean_end_lane  std_end_lane  min_end_lane  25%_end_lane  \
id
0              1.0       88.00000           NaN      88.00000      88.00000
1              1.0      105.00000           NaN     105.00000     105.00000
2              1.0      113.80592           NaN     113.80592     113.80592
3              1.0      124.00000           NaN     124.00000     124.00000
4              1.0      131.00000           NaN     131.00000     131.00000

    50%_end_lane  75%_end_lane  max_end_lane
id
0       88.00000      88.00000      88.00000
1      105.00000     105.00000     105.00000
2      113.80592     113.80592     113.80592
3      124.00000     124.00000     124.00000
4      131.00000     131.00000     131.00000
```

[745]:

```
avg_time_diff = time_diff_df['min_end_lane'] - time_diff_df['min_enter_lane']
Avg_tt = avg_time_diff.mean()
print('Average Travelling Time =', Avg_tt)
```

```
Average Travelling Time = 90.3553481568357
```

[746]:

```
Avg_speed_1 = l.totalLength()/Avg_tt
print('Average Speed', Avg_speed, 'm/s')
```

```
Average Speed 33.202240500392996 m/s
```

Method- 2

[747]:

```
def Average_tt():
    ids = df.id.unique()
    tt = []
    for j in ids:
        df_id = df[df['id'] == j]
        start = df_id[df_id['event'] == "enter lane"]
        end = df_id[df_id['event'] == "end"]
        if(len(end.index)!=0):
            tt.append(end.iloc[-1]['t'] - start.iloc[0]['t'])
    return tt
```

[748]:

```
travelling_time = Average_tt()
A_tt = sum(travelling_time) / len(travelling_time)
print('Average Travelling Time =', A_tt)
```

```
Average Travelling Time = 90.3553481568357
```

[749]:

```
Avg_speed_2 = l.totalLength()/A_tt
print('Average Speed', Avg_speed, 'm/s')
```

```
Average Speed 33.202240500392996 m/s
```

12.0.3 Throughput

[750]:

```
def throughput():
    leave_ln = df[df.event == 'end']
    ll = leave_ln.groupby(['id'])
    leave_ln_final = ll.last().sort_index().reset_index()
    T_min = leave_ln.t.min()
    T_max = leave_ln.t.max()
    no_of_vehicles = len(leave_ln)
    Throughput = (no_of_vehicles/(T_max - T_min))*3600
    return Throughput
print('Throughput in cars/hours = ', throughput())
```

```
Throughput in cars/hours =  485.7476635514019
```

12.0.4 Traffic Density

[751]:

```
Traffic_density = Throughput/Avg_speed_1
print('Traffic Density = ', Traffic_density)
```

```
Traffic Density =  6.745795691525602
```

[ ]:

```

```

13 Task-2

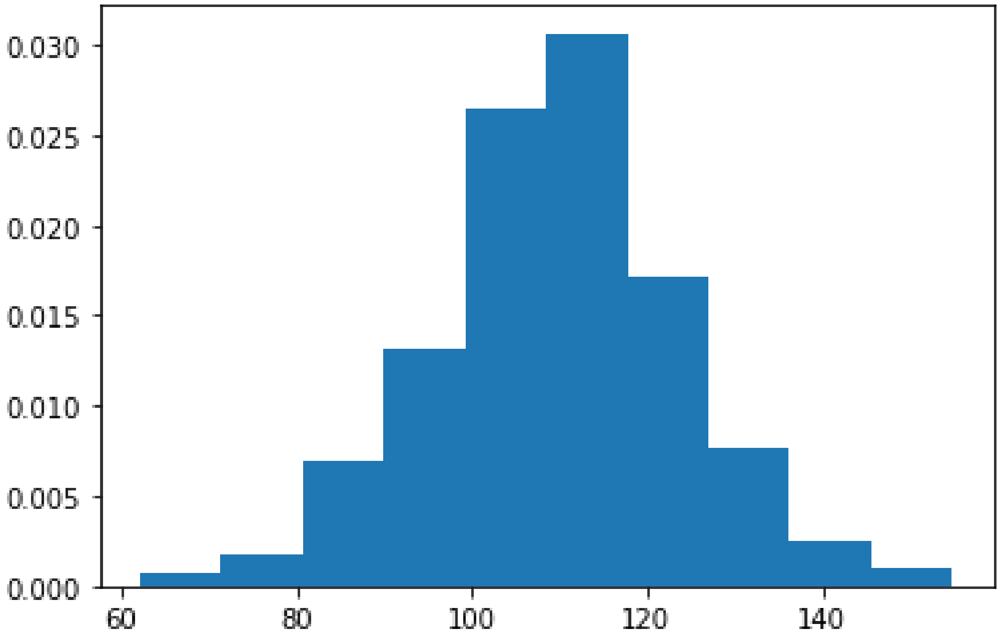
Introducing the freemotorwaySpeed() function

[696]:

```
#Introducing the freemotorway speed function() to calculate the speeds of the␣
 ↪vehicles
free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
quantiles = np.cumsum([0, 0.003, 0.014, 0.052, 0.148, 0.27, 0.309, 0.143, 0.
 ↪048, 0.01, 0.003])

def random_speed():
    u = random.random() # generates uniformly distributed random number 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)
```

[697]:

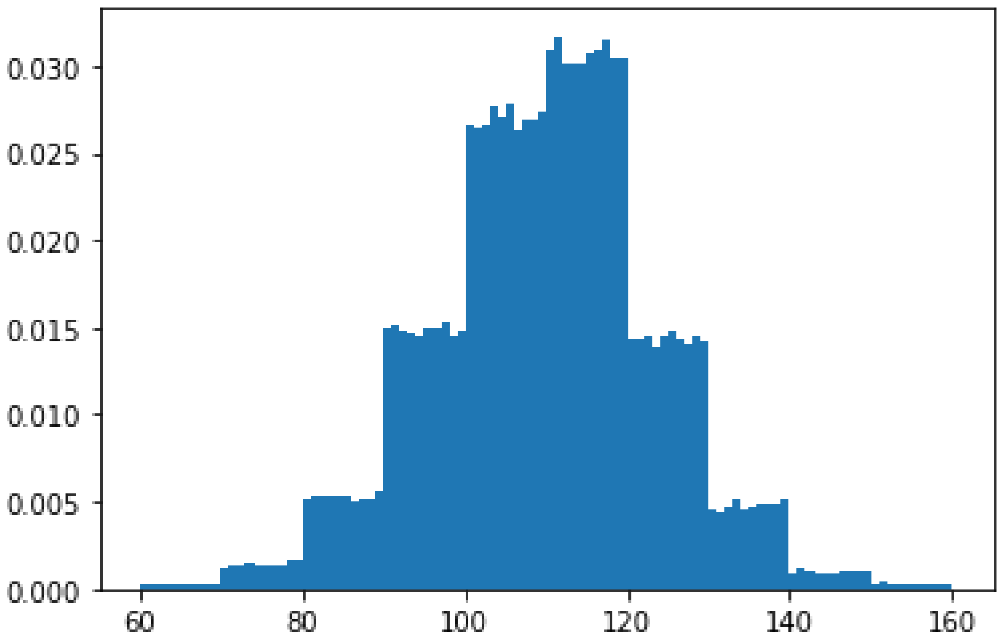
```
#Checking the distribution of speeds
random.seed(0)
speeds = [ random_speed() for i in range(1200)]
hist = plt.hist(speeds, bins=10, density=True)
```



This simple approach generates however a stepwise distribution function, which may have undesired side effects for large sample sets, as we can see in this example:

[698]:

```
random.seed(0)
speeds = [ random_speed() for i in range(100000)]
hist = plt.hist(speeds, bins=100, density=True)
```



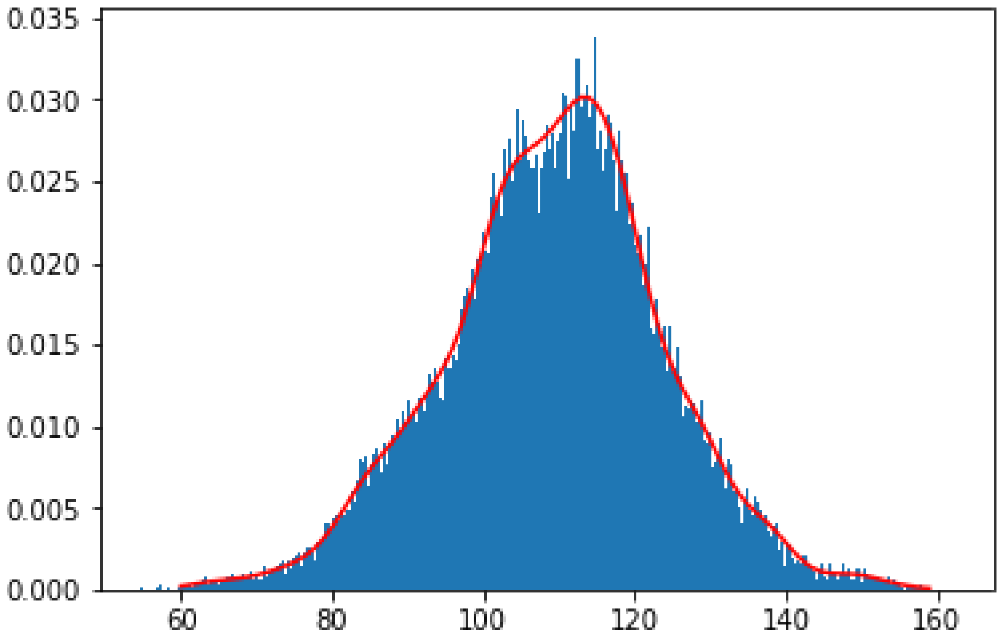
[699]:
```
# We now define the gaussian kernel that matches the distribution
random.seed(0)
speeds = [ random_speed() for i in range(1200)]
kernel = stats.gaussian_kde(speeds)
```

[700]:
```
vel = np.arange(30, 191)
q = [ kernel.integrate_box_1d(30, i) for i in vel ]

def freeMotorwaySpeed():
    u = random.random() # generates uniformly distributed random number between␣
 ↪0 and 1
    for i in range(len(q)):
        if u<q[i+1]:
            p = (u-q[i])/(q[i+1]-q[i])
            # return (free_speed[i+1]+free_speed[i])/
 ↪2*p+(1-p)*(free_speed[i+1]+free_speed[i+2])/2
            return vel[i]*p + vel[i+1]*(1-p)
```

[701]:
```
random.seed(0)
rspeeds = [ freeMotorwaySpeed() for i in range(100000) ]
```

[702]:
```
#Checking the distribution of freemotorway function
h = plt.hist(rspeeds, bins=1000, density=True)
x = np.arange(60, 160, 1)
y = kernel(x)
```

```
plot = plt.plot(x, y, color='red')
```



Checking the ranges of the expovariate and the uniform distribution

[703]:
```
IAT = 18
iat_e = [ random.expovariate(1.0/IAT) for i in range(3000) ]
print(max(iat_e), min(iat_e))
```

```
155.3055767808769 0.004485859854781841
```

[704]:
```
IAT = 20
iat_u = [random.uniform(IAT/10, IAT+10) for i in range(3000)]
print(max(iat_u), min(iat_u))
```

```
29.990512481213685 2.024546399521641
```

[ ]:
```
```

Incorporating chooseLane(), chooseIAT() and freeMotorwaySpeed() into simulation

[832]:
```
VMAX = 120/3.6
N = 2000
IAT_slow = 18 #Average interarrival time for the slow lane
IAT_fast = 13  #Average interarrival time for the fast lane
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 3000, 1)
random.seed(42)
```

```
lane_choice = [chooseLane([l, r]) for i in range(N)]
iat_slow = [random.uniform(IAT_slow/10, IAT_slow+10) for i in range(N)]
iat_fast = [random.uniform(IAT_fast/10, IAT_slow+10) for i in range(N)]
l = Lane(3000, VMAX)
r = l.widenRight()

t0 = 0
for i in range(N):
    CYCLES = random.randint(4, 8)
    times = randomIntervals(CYCLES)
    speed = [freeMotorwaySpeed()/3.6 for i in range(N)]   #Using the free␣
 ↪motorway speed function to generate the speeds
    lane_choice = chooseLane([l, r])

    if lane_choice == r:
        t0 += iat_fast[i]
        v = Vehicle(env, rec, startingLane = lane_choice, t0=t0, dx0=speed[-1],␣
 ↪t=times, v=speed)
    elif lane_choice == l:
        t0 += iat_slow[i]
        v = Vehicle(env, rec, startingLane = lane_choice, t0=t0, dx0=speed[-1],␣
 ↪t=times, v=speed)
    v.traceOvertake = True
#     v.traceSurround = True
rec.run()
```

```
t=    5.0s Overtaking v0 returns to slow lane at x=   15.9m
t=   62.0s Overtaking v2 returns to slow lane at x=1,102.4m
t=  112.0s Overtaking v7 returns to slow lane at x=   15.8m
t=  139.0s Overtaking v5 overtakes v4 at x=2,513.3m
t=  146.0s Overtaking v10 returns to slow lane at x=   26.6m
t=  151.0s Overtaking v5 returns to slow lane at x=2,955.8m
t=  175.0s Overtaking v9 overtakes v8 at x=1,157.6m
t=  180.0s Overtaking v12 returns to slow lane at x=    4.6m
t=  188.0s Overtaking v12 overtakes v11 at x=  314.5m
t=  221.0s Overtaking v9 returns to slow lane at x=2,829.5m
t=  256.0s Overtaking v12 returns to slow lane at x=2,740.5m
t=  282.0s Overtaking v19 returns to slow lane at x=    7.1m
t=  286.0s Overtaking v16 overtakes v15 at x=1,423.3m
t=  330.0s Overtaking v16 returns to slow lane at x=2,946.9m
t=  339.0s Overtaking v21 returns to slow lane at x=1,247.8m
t=  346.0s Overtaking v19 overtakes v18 at x=2,390.1m
t=  358.0s Overtaking v22 overtakes v20 at x=1,503.8m
t=  421.0s Overtaking v26 overtakes v25 at x=  867.8m
t=  430.0s Overtaking v28 returns to slow lane at x=   10.8m
t=  447.0s Overtaking v30 overtakes v29 at x=  142.6m
t=  453.0s Overtaking v26 returns to slow lane at x=2,056.4m
```

```
t=  467.0s Overtaking v26 overtakes v24 at x=2,599.3m
t=  476.0s Overtaking v28 overtakes v27 at x=1,392.8m
t=  477.0s Overtaking v26 returns to slow lane at x=2,991.4m
t=  479.0s Overtaking v30 returns to slow lane at x=1,348.5m
t=  498.0s Overtaking v30 overtakes v27 at x=1,958.0m
t=  512.0s Overtaking v32 returns to slow lane at x=1,655.5m
t=  519.0s Overtaking v36 returns to slow lane at x=   10.9m
t=  520.0s Overtaking v28 returns to slow lane at x=2,860.1m
t=  525.0s Overtaking v36 overtakes v35 at x=  174.1m
t=  528.0s Overtaking v30 returns to slow lane at x=2,955.4m
t=  530.0s Overtaking v37 returns to slow lane at x=   15.3m
t=  558.0s Overtaking v39 returns to slow lane at x=   29.6m
t=  561.0s Overtaking v34 overtakes v33 at x=2,069.4m
t=  569.0s Overtaking v36 returns to slow lane at x=1,514.1m
t=  574.0s Overtaking v34 returns to slow lane at x=2,575.4m
t=  595.0s Overtaking v39 overtakes v38 at x=1,348.8m
t=  607.0s Overtaking v42 overtakes v41 at x=   32.4m
t=  637.0s Overtaking v39 returns to slow lane at x=2,944.2m
t=  637.0s Overtaking v44 returns to slow lane at x=   12.1m
t=  679.0s Overtaking v42 returns to slow lane at x=2,560.5m
t=  680.0s Overtaking v47 returns to slow lane at x=   13.4m
t=  687.0s Overtaking v45 overtakes v44 at x=1,166.0m
t=  688.0s Overtaking v47 overtakes v46 at x=  323.3m
t=  702.0s Overtaking v48 returns to slow lane at x=    4.3m
t=  705.0s Overtaking v47 returns to slow lane at x=1,029.6m
t=  712.0s Overtaking v45 returns to slow lane at x=2,139.0m
t=  717.0s Overtaking v49 returns to slow lane at x=   35.7m
t=  727.0s Overtaking v45 overtakes v43 at x=2,742.0m
t=  735.0s Overtaking v51 returns to slow lane at x=   24.8m
t=  752.0s Overtaking v49 overtakes v48 at x=1,382.7m
t=  758.0s Overtaking v51 overtakes v50 at x=  965.0m
t=  771.0s Overtaking v53 returns to slow lane at x=    5.4m
t=  781.0s Overtaking v51 returns to slow lane at x=1,918.0m
t=  785.0s Overtaking v53 overtakes v52 at x=  547.4m
t=  816.0s Overtaking v53 returns to slow lane at x=1,781.0m
t=  835.0s Overtaking v56 overtakes v55 at x=  397.6m
t=  858.0s Overtaking v58 returns to slow lane at x=    3.1m
t=  880.0s Overtaking v59 returns to slow lane at x=   23.2m
t=  881.0s Overtaking v56 returns to slow lane at x=1,840.4m
t=  887.0s Overtaking v57 overtakes v55 at x=1,705.3m
t=  912.0s Overtaking v57 returns to slow lane at x=2,574.9m
t=  958.0s Overtaking v64 returns to slow lane at x=   19.4m
t=  968.0s Overtaking v65 returns to slow lane at x=   18.2m
t=  973.0s Overtaking v65 overtakes v64 at x=  184.9m
t=  997.0s Overtaking v62 overtakes v61 at x=2,031.8m
t=  999.0s Overtaking v65 returns to slow lane at x=1,127.5m
t=1,018.0s Overtaking v68 returns to slow lane at x=    9.7m
t=1,023.0s Overtaking v66 overtakes v64 at x=1,476.0m
```

```
t=1,024.0s Overtaking v62 returns to slow lane at x=2,970.9m
t=1,024.0s Overtaking v69 returns to slow lane at x=   24.4m
t=1,047.0s Overtaking v66 returns to slow lane at x=2,407.7m
t=1,113.0s Overtaking v73 overtakes v72 at x=  535.8m
t=1,138.0s Overtaking v73 returns to slow lane at x=1,471.3m
t=1,186.0s Overtaking v75 overtakes v74 at x=1,955.5m
t=1,188.0s Overtaking v80 returns to slow lane at x=   26.0m
t=1,193.0s Overtaking v80 overtakes v79 at x=  223.2m
t=1,209.0s Overtaking v80 returns to slow lane at x=  905.3m
t=1,242.0s Overtaking v81 overtakes v79 at x=1,477.6m
t=1,247.0s Overtaking v80 overtakes v78 at x=2,571.1m
t=1,270.0s Overtaking v81 returns to slow lane at x=2,516.1m
t=1,319.0s Overtaking v89 returns to slow lane at x=   22.5m
t=1,375.0s Overtaking v88 overtakes v87 at x=2,334.2m
t=1,393.0s Overtaking v88 returns to slow lane at x=2,974.6m
t=1,397.0s Overtaking v93 returns to slow lane at x=   22.2m
t=1,441.0s Overtaking v96 returns to slow lane at x=   30.0m
t=1,450.0s Overtaking v92 overtakes v91 at x=2,248.1m
t=1,469.0s Overtaking v92 returns to slow lane at x=2,961.5m
t=1,473.0s Overtaking v95 overtakes v94 at x=1,720.6m
t=1,506.0s Overtaking v95 returns to slow lane at x=2,925.2m
t=1,568.0s Overtaking v103 returns to slow lane at x=   30.3m
t=1,630.0s Overtaking v106 returns to slow lane at x=   12.3m
t=1,691.0s Overtaking v105 overtakes v104 at x=2,682.8m
t=1,699.0s Overtaking v105 returns to slow lane at x=2,972.0m
t=1,727.0s Overtaking v110 overtakes v109 at x=  975.8m
t=1,742.0s Overtaking v113 returns to slow lane at x=   16.9m
t=1,779.0s Overtaking v110 returns to slow lane at x=2,716.9m
t=1,786.0s Overtaking v113 overtakes v112 at x=1,651.8m
t=1,800.0s Overtaking v117 returns to slow lane at x=   27.1m
t=1,804.0s Overtaking v117 overtakes v116 at x=  146.9m
t=1,808.0s Overtaking v113 returns to slow lane at x=2,488.4m
t=1,835.0s Overtaking v117 returns to slow lane at x=1,116.8m
t=1,848.0s Overtaking v115 overtakes v114 at x=2,478.5m
t=1,861.0s Overtaking v115 returns to slow lane at x=2,972.2m
t=1,869.0s Overtaking v124 returns to slow lane at x=   22.5m
t=1,881.0s Overtaking v123 overtakes v122 at x=  597.1m
t=1,910.0s Overtaking v124 overtakes v122 at x=1,305.0m
t=1,919.0s Overtaking v123 returns to slow lane at x=1,915.3m
t=1,968.0s Overtaking v129 returns to slow lane at x=   21.0m
t=1,992.0s Overtaking v130 returns to slow lane at x=    0.6m
t=2,021.0s Overtaking v133 returns to slow lane at x=    6.8m
t=2,040.0s Overtaking v132 overtakes v131 at x=1,265.4m
t=2,048.0s Overtaking v134 returns to slow lane at x=    4.2m
t=2,058.0s Overtaking v130 overtakes v129 at x=2,653.2m
t=2,067.0s Overtaking v130 returns to slow lane at x=2,996.6m
t=2,070.0s Overtaking v132 returns to slow lane at x=2,219.3m
t=2,193.0s Overtaking v139 overtakes v138 at x=2,163.5m
```

```
t=2,219.0s Overtaking v139 returns to slow lane at x=2,982.3m
t=2,222.0s Overtaking v141 overtakes v140 at x=2,471.9m
t=2,222.0s Overtaking v145 returns to slow lane at x=   11.2m
t=2,235.0s Overtaking v141 returns to slow lane at x=2,946.7m
t=2,250.0s Overtaking v146 returns to slow lane at x=   18.6m
t=2,327.0s Overtaking v150 returns to slow lane at x=   20.1m
t=2,370.0s Overtaking v153 returns to slow lane at x=   11.8m
t=2,376.0s Overtaking v154 overtakes v153 at x=    4.9m
t=2,381.0s Overtaking v150 overtakes v149 at x=2,069.3m
t=2,408.0s Overtaking v150 returns to slow lane at x=2,972.6m
t=2,428.0s Overtaking v157 returns to slow lane at x=   25.3m
t=2,452.0s Overtaking v154 returns to slow lane at x=2,668.9m
Crash p154 into p153 at t=2453.000 x= 2701.7
t=2,470.0s Overtaking v159 returns to slow lane at x=    1.6m
t=2,475.0s Overtaking v155 overtakes v154 at x=2,506.6m
t=2,484.0s Overtaking v155 returns to slow lane at x=2,807.4m
t=2,490.0s Overtaking v156 overtakes v154 at x=2,519.0m
t=2,499.0s Overtaking v156 returns to slow lane at x=2,810.2m
t=2,501.0s Overtaking v157 overtakes v154 at x=2,525.0m
t=2,501.0s Overtaking v163 overtakes v162 at x=   28.3m
t=2,508.0s Overtaking v157 returns to slow lane at x=2,790.6m
t=2,512.0s Overtaking v161 overtakes v160 at x=  761.4m
t=2,522.0s Overtaking v163 returns to slow lane at x=  769.4m
t=2,523.0s Overtaking v158 overtakes v154 at x=2,514.1m
t=2,527.0s Overtaking v164 returns to slow lane at x=    9.1m
t=2,532.0s Overtaking v158 returns to slow lane at x=2,799.5m
t=2,537.0s Overtaking v161 returns to slow lane at x=1,657.0m
t=2,541.0s Overtaking v163 overtakes v160 at x=1,482.8m
t=2,549.0s Overtaking v159 overtakes v154 at x=2,526.7m
t=2,557.0s Overtaking v159 returns to slow lane at x=2,795.8m
t=2,559.0s Overtaking v163 returns to slow lane at x=2,201.6m
t=2,560.0s Overtaking v161 overtakes v154 at x=2,525.1m
t=2,567.0s Overtaking v161 returns to slow lane at x=2,805.1m
t=2,577.0s Overtaking v160 overtakes v154 at x=2,543.2m
t=2,588.0s Overtaking v162 overtakes v154 at x=2,530.8m
t=2,589.0s Overtaking v160 returns to slow lane at x=2,865.1m
t=2,598.0s Overtaking v162 returns to slow lane at x=2,853.1m
t=2,601.0s Overtaking v164 overtakes v154 at x=2,529.2m
t=2,614.0s Overtaking v164 returns to slow lane at x=2,967.2m
t=2,619.0s Overtaking v168 overtakes v167 at x=1,361.7m
t=2,636.0s Overtaking v165 overtakes v154 at x=2,534.2m
t=2,644.0s Overtaking v165 returns to slow lane at x=2,817.0m
t=2,648.0s Overtaking v172 returns to slow lane at x=   15.3m
t=2,651.0s Overtaking v166 overtakes v154 at x=2,527.3m
t=2,655.0s Overtaking v167 overtakes v154 at x=2,520.5m
t=2,660.0s Overtaking v166 returns to slow lane at x=2,803.4m
t=2,673.0s Overtaking v169 overtakes v154 at x=2,529.1m
t=2,707.0s Overtaking v170 overtakes v154 at x=2,505.1m
```

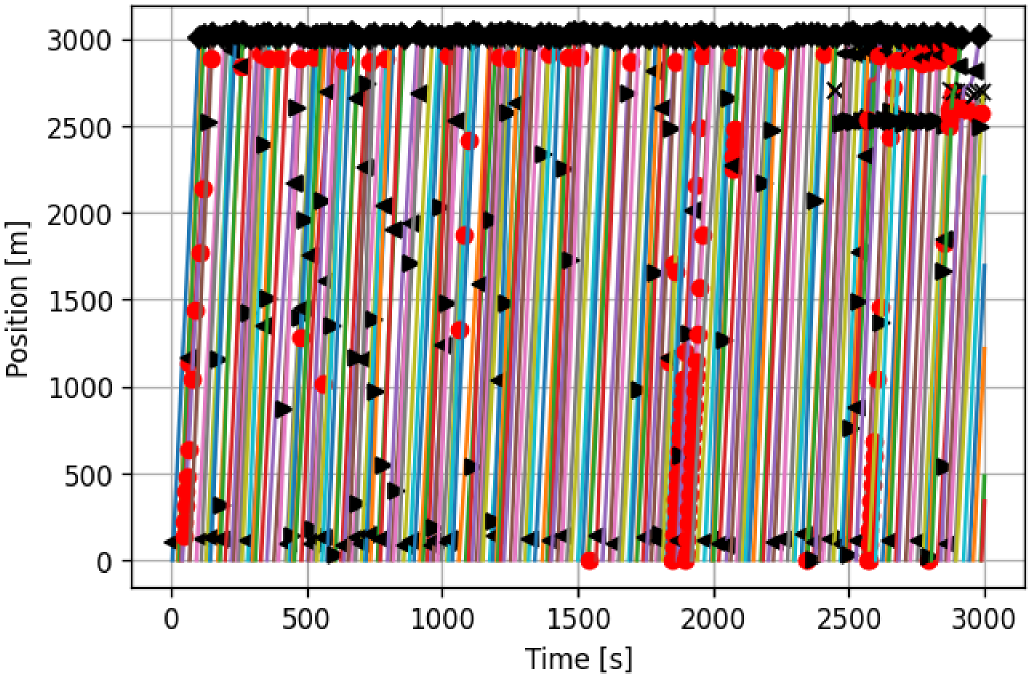
```
t=2,716.0s Overtaking v171 overtakes v154 at x=2,520.7m
t=2,724.0s Overtaking v171 returns to slow lane at x=2,800.9m
t=2,724.0s Overtaking v172 overtakes v154 at x=2,532.5m
t=2,752.0s Overtaking v173 overtakes v154 at x=2,522.7m
t=2,754.0s Overtaking v177 returns to slow lane at x=    9.6m
t=2,761.0s Overtaking v174 overtakes v154 at x=2,515.4m
t=2,769.0s Overtaking v174 returns to slow lane at x=2,789.3m
t=2,790.0s Overtaking v175 overtakes v154 at x=2,523.0m
t=2,797.0s Overtaking v181 overtakes v180 at x=   24.1m
t=2,798.0s Overtaking v175 returns to slow lane at x=2,795.4m
t=2,815.0s Overtaking v176 overtakes v154 at x=2,513.1m
t=2,827.0s Overtaking v177 overtakes v154 at x=2,524.2m
t=2,835.0s Overtaking v177 returns to slow lane at x=2,805.2m
t=2,848.0s Overtaking v181 returns to slow lane at x=1,791.9m
t=2,853.0s Overtaking v182 overtakes v180 at x=1,657.6m
t=2,856.0s Overtaking v184 overtakes v183 at x=  536.8m
t=2,858.0s Overtaking v185 returns to slow lane at x=    2.3m
t=2,860.0s Overtaking v178 overtakes v154 at x=2,503.3m
Crash p179 into p154 at t=2873.000 x= 2698.4
t=2,874.0s Overtaking v178 returns to slow lane at x=2,937.5m
Crash p181 into p179 at t=2890.000 x= 2694.6
t=2,900.0s Overtaking v182 returns to slow lane at x=2,795.0m
Crash p180 into p181 at t=2902.000 x= 2690.9
Crash p183 into p154 at t=2923.000 x= 2698.9
t=2,959.0s Overtaking v184 returns to slow lane at x=2,787.8m
Crash p185 into p186 at t=2964.000 x= 2671.7
Crash p187 into p180 at t=2978.000 x= 2690.0
t=2,987.0s Overtaking v188 overtakes v185 at x=2,486.4m
Crash p188 into p181 at t=2996.000 x= 2693.2
```

```
[833]: rec.getData()
```

```
[833]:
                 t        x          v         a   id lane oldLane      pos  \
0         4.437688        0  28.304996         0    0    1    None        0
1         5.000000    15.92  28.306700   0.00621    0    1    None    15.92
2         5.000000    15.92  28.306700   0.00621    0    1    None    15.92
3         5.000000    15.92  28.306700   0.00621    0    0       1    15.92
4         6.000000    44.73  29.306700         1    0    0       1    44.73
…            …      …        …       …  …  …     …      …
20005  3000.000000  2204.33  25.452000 -0.084943  189    0    None  2204.33
20006  3000.000000  1693.64  29.373500 -0.030166  190    0    None  1693.64
20007  3000.000000  1217.19  29.504400 -0.004358  191    0    None  1217.19
20008  3000.000000   484.69  33.464900 -0.250449  192    0    None   484.69
20009  3000.000000   340.37  31.701400 -0.095266  193    0    None   340.37

             event
0       enter lane
```

```
1            timer
2      change slow
3       enter lane
4            timer
…              …
20005        timer
20006        timer
20007        timer
20008        timer
20009        timer

[20010 rows x 9 columns]
```

[834]:
```
rec.plot('t', 'x')
```



[835]:
```
df = rec.getData()
```

13.1 Average travelling time and speeds

[836]:
```
travelling_time = Average_tt()
A_tt = sum(travelling_time) / len(travelling_time)
print('Average Travelling Time =', A_tt)
```

```
Average Travelling Time = 97.71498158680153
```

[838]:
```
Avg_speed_2 = l.totalLength()/A_tt
print('Average Speed', Avg_speed_2, 'm/s')
```

```
Average Speed 30.701535744905808 m/s
```

13.2 Throughput

[839]:
```
Throughput = throughput()
print('Throughput in cars/hours = ', Throughput)
```

```
Throughput in cars/hours =  223.97553091654794
```

13.3 Traffic Density

[840]:
```
Traffic_density = Throughput/Avg_speed_1
print('Traffic Density = ', Traffic_density)
```

```
Traffic Density =  6.745795691525602
```

[ ]:
```

```

Varying speed and interarrival times - using expovariate distribution for calculating inter-arrival time and randomSpeedvariation function for velocities

[791]:
```
VMAX = 120/3.6
N = 2000 # number of points
IAT =  18# average interarrival time
random.seed(13)
env = simpy.Environment()
rec = SimpleRecorder(env, 0, 1800, 1)
iat = [ random.expovariate(1.0/IAT) for i in range(N) ]
# iat = [random.uniform(IAT/10, IAT+10) for i in range(500)]
l = Lane(3000, VMAX)
r = l.widenRight()
print('l', l)
print('r', r)
t0 = 0
for i in range(N):
    CYCLES = random.randint(4, 8)
    times = randomIntervals(CYCLES)
    speed = randomSpeedVariation(VMAX, CYCLES)
    t0 += iat[i]
    v = Vehicle(env, rec, startingLane=l, t0=t0, dx0=speed[-1], t=times,␣
 ↪v=speed)
    v.traceOvertake = True
#     v.traceSurround = True
rec.run()
```

```
l [0 3000m R:1]
r [1 3000m L:0]
```

```
t=  206.0s Overtaking v12 overtakes v11 at x=2,019.6m
t=  230.0s Overtaking v12 returns to slow lane at x=2,925.5m
t=  534.0s Overtaking v26 overtakes v25 at x=2,597.2m
t=  541.0s Overtaking v26 returns to slow lane at x=2,855.4m
t=  606.0s Overtaking v31 overtakes v30 at x=1,816.8m
t=  636.0s Overtaking v31 returns to slow lane at x=2,896.3m
t=  648.0s Overtaking v35 overtakes v34 at x=2,186.0m
t=  668.0s Overtaking v35 returns to slow lane at x=2,923.0m
t=  837.0s Overtaking v48 overtakes v47 at x=   32.0m
t=  910.0s Overtaking v48 returns to slow lane at x=2,622.4m
Crash p48 into p47 at t=911.000 x= 2657.2
t=  920.0s Overtaking v49 overtakes v48 at x=2,492.8m
t=  927.0s Overtaking v49 returns to slow lane at x=2,758.1m
t=  931.0s Overtaking v55 overtakes v54 at x=1,174.8m
t=  936.0s Overtaking v50 overtakes v48 at x=2,462.5m
t=  944.0s Overtaking v50 returns to slow lane at x=2,757.4m
t=  945.0s Overtaking v51 overtakes v48 at x=2,464.5m
t=  950.0s Overtaking v52 overtakes v48 at x=2,481.4m
t=  953.0s Overtaking v51 returns to slow lane at x=2,750.7m
t=  958.0s Overtaking v52 returns to slow lane at x=2,767.6m
t=  960.0s Overtaking v53 overtakes v48 at x=2,482.1m
t=  968.0s Overtaking v53 returns to slow lane at x=2,768.6m
t=  974.0s Overtaking v55 returns to slow lane at x=2,787.1m
t=  977.0s Overtaking v56 overtakes v48 at x=2,485.8m
t=  981.0s Overtaking v57 overtakes v48 at x=2,465.7m
t=  984.0s Overtaking v58 overtakes v48 at x=2,495.8m
t=  985.0s Overtaking v56 returns to slow lane at x=2,781.3m
t=  989.0s Overtaking v57 returns to slow lane at x=2,760.9m
t=  992.0s Overtaking v58 returns to slow lane at x=2,787.2m
t=1,001.0s Overtaking v59 overtakes v48 at x=2,486.6m
t=1,011.0s Overtaking v59 returns to slow lane at x=2,864.1m
t=1,058.0s Overtaking v60 overtakes v48 at x=2,483.9m
t=1,065.0s Overtaking v60 returns to slow lane at x=2,741.1m
t=1,068.0s Overtaking v61 overtakes v48 at x=2,487.1m
t=1,075.0s Overtaking v61 returns to slow lane at x=2,753.5m
t=1,090.0s Overtaking v62 overtakes v48 at x=2,464.2m
t=1,098.0s Overtaking v62 returns to slow lane at x=2,751.3m
t=1,140.0s Overtaking v63 overtakes v48 at x=2,486.0m
t=1,143.0s Overtaking v64 overtakes v48 at x=2,493.4m
t=1,147.0s Overtaking v63 returns to slow lane at x=2,741.3m
t=1,150.0s Overtaking v65 overtakes v48 at x=2,478.6m
t=1,151.0s Overtaking v64 returns to slow lane at x=2,771.2m
t=1,158.0s Overtaking v65 returns to slow lane at x=2,746.9m
t=1,172.0s Overtaking v66 overtakes v48 at x=2,473.9m
t=1,180.0s Overtaking v66 returns to slow lane at x=2,767.7m
t=1,202.0s Overtaking v67 overtakes v48 at x=2,480.1m
t=1,203.0s Overtaking v70 overtakes v69 at x=1,465.4m
t=1,209.0s Overtaking v67 returns to slow lane at x=2,741.3m
```

```
t=1,220.0s Overtaking v68 overtakes v48 at x=2,473.0m
t=1,227.0s Overtaking v68 returns to slow lane at x=2,739.9m
t=1,227.0s Overtaking v69 overtakes v48 at x=2,465.0m
t=1,235.0s Overtaking v69 returns to slow lane at x=2,751.4m
t=1,238.0s Overtaking v70 returns to slow lane at x=2,768.7m
t=1,273.0s Overtaking v71 overtakes v48 at x=2,479.3m
t=1,281.0s Overtaking v71 returns to slow lane at x=2,773.1m
t=1,312.0s Overtaking v72 overtakes v48 at x=2,488.1m
t=1,319.0s Overtaking v72 returns to slow lane at x=2,751.1m
t=1,344.0s Overtaking v73 overtakes v48 at x=2,488.6m
t=1,350.0s Overtaking v74 overtakes v48 at x=2,460.1m
t=1,351.0s Overtaking v73 returns to slow lane at x=2,743.2m
t=1,359.0s Overtaking v74 returns to slow lane at x=2,771.5m
t=1,382.0s Overtaking v75 overtakes v48 at x=2,475.3m
t=1,389.0s Overtaking v76 overtakes v48 at x=2,474.6m
t=1,390.0s Overtaking v75 returns to slow lane at x=2,757.2m
t=1,397.0s Overtaking v76 returns to slow lane at x=2,762.6m
t=1,412.0s Overtaking v77 overtakes v48 at x=2,478.4m
t=1,416.0s Overtaking v78 overtakes v48 at x=2,488.5m
t=1,420.0s Overtaking v77 returns to slow lane at x=2,766.1m
t=1,424.0s Overtaking v78 returns to slow lane at x=2,769.3m
t=1,473.0s Overtaking v79 overtakes v48 at x=2,460.3m
t=1,481.0s Overtaking v79 returns to slow lane at x=2,766.8m
t=1,492.0s Overtaking v80 overtakes v48 at x=2,465.6m
t=1,500.0s Overtaking v80 returns to slow lane at x=2,762.7m
t=1,514.0s Overtaking v81 overtakes v48 at x=2,475.3m
t=1,521.0s Overtaking v81 returns to slow lane at x=2,740.6m
t=1,523.0s Overtaking v82 overtakes v48 at x=2,486.1m
t=1,531.0s Overtaking v82 returns to slow lane at x=2,758.7m
t=1,540.0s Overtaking v83 overtakes v48 at x=2,475.1m
t=1,548.0s Overtaking v83 returns to slow lane at x=2,761.0m
t=1,548.0s Overtaking v84 overtakes v48 at x=2,470.1m
t=1,555.0s Overtaking v84 returns to slow lane at x=2,748.8m
t=1,570.0s Overtaking v85 overtakes v48 at x=2,490.4m
t=1,573.0s Overtaking v93 overtakes v92 at x=   13.4m
t=1,576.0s Overtaking v94 overtakes v92 at x=   70.1m
t=1,577.0s Overtaking v85 returns to slow lane at x=2,741.5m
t=1,580.0s Overtaking v86 overtakes v48 at x=2,457.4m
t=1,588.0s Overtaking v86 returns to slow lane at x=2,745.6m
t=1,602.0s Overtaking v87 overtakes v48 at x=2,481.7m
t=1,610.0s Overtaking v87 returns to slow lane at x=2,776.8m
t=1,611.0s Overtaking v88 overtakes v48 at x=2,462.0m
t=1,616.0s Overtaking v89 overtakes v48 at x=2,490.8m
t=1,619.0s Overtaking v88 returns to slow lane at x=2,748.0m
t=1,623.0s Overtaking v89 returns to slow lane at x=2,743.1m
t=1,624.0s Overtaking v90 overtakes v48 at x=2,483.0m
t=1,630.0s Overtaking v94 returns to slow lane at x=1,866.2m
t=1,632.0s Overtaking v90 returns to slow lane at x=2,764.3m
```

```
t=1,637.0s Overtaking v93 returns to slow lane at x=2,209.4m
Crash p102 into p101 at t=1642.000 x=   10.4
t=1,644.0s Overtaking v91 overtakes v48 at x=2,477.0m
t=1,652.0s Overtaking v91 returns to slow lane at x=2,766.1m
Crash p93 into p47 at t=1652.000 x= 2659.4
Crash p94 into p93 at t=1673.000 x= 2659.2
Crash p95 into p48 at t=1675.000 x= 2656.0
t=1,704.0s Overtaking v99 overtakes v98 at x=2,436.3m
Crash p98 into p95 at t=1713.000 x= 2654.3
Crash p100 into p98 at t=1725.000 x= 2651.8
Crash p103 into p102 at t=1753.000 x=    7.8
Crash p105 into p104 at t=1769.000 x=  137.8
Crash p106 into p105 at t=1784.000 x=  134.6
Crash p107 into p108 at t=1790.000 x=  121.2
```

[794]:

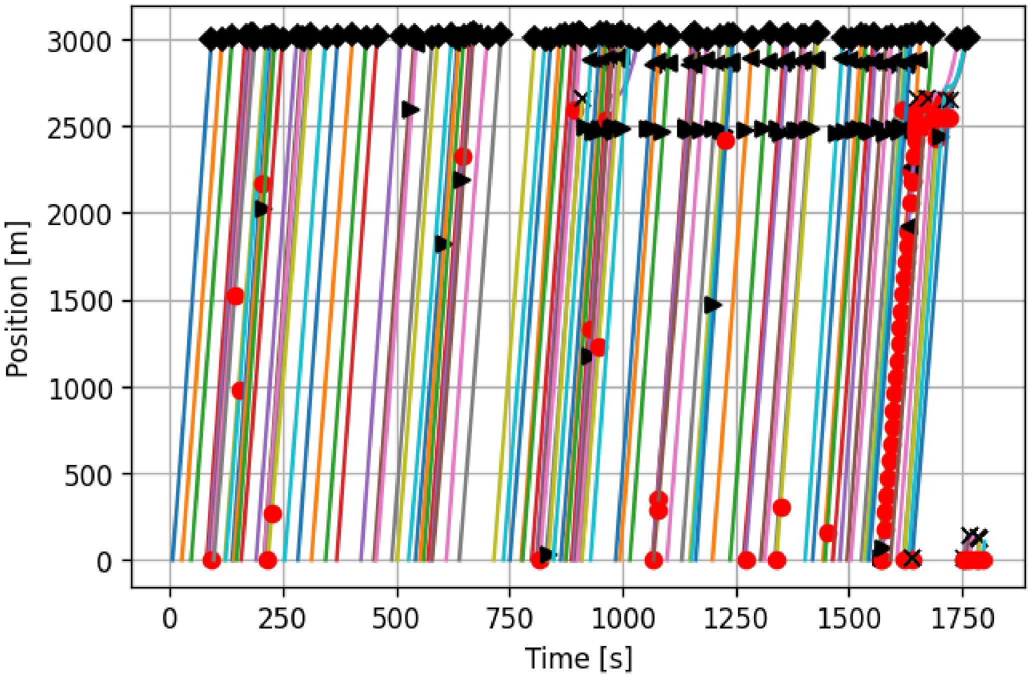
```
df = rec.getData()
df.head()
```

[794]:

```
         t       x          v         a  id  lane  oldLane     pos        event
0  5.39579       0  31.536818         0   0     0     None       0   enter lane
1  6.00000   19.06  31.545800  0.029723   0     0     None   19.06        timer
2  7.00000   50.63  31.600100  0.078917   0     0     None   50.63        timer
3  8.00000   82.28  31.703600   0.12811   0     0     None   82.28        timer
4  9.00000  114.06  31.848800  0.150028   0     0     None  114.06        timer
```

[795]:

```
rec.plot('t', 'x')
```



```
[796]: Throughput = throughput()
       print('Throughput in cars/hours = ', Throughput)
```

```
Throughput in cars/hours =  202.5491674621294
```

```
[798]: travelling_time = Average_tt()
       A_tt = sum(travelling_time) / len(travelling_time)
       print('Average Travelling Time =', A_tt)
```

```
Average Travelling Time = 91.65743588886406
```

```
[800]: Avg_speed_3 = l.totalLength()/A_tt
       print('Average Speed', Avg_speed_3, 'm/s')
```

```
Average Speed 32.73056867571053 m/s
```

Incorporating the different vehicle types

```
[820]: def chooseVehicle(VehicleList):
           vehicle = random.choices(VehicleList, [0.80, 0.20])[0]
           return vehicle
```

```
[821]: choice_v = [chooseVehicle(['electrical', 'diesel']) for i in range(20)]
       print(choice_v)
```

```
['electrical', 'electrical', 'electrical', 'electrical', 'electrical',
'electrical', 'electrical', 'electrical', 'electrical', 'diesel', 'electrical',
'electrical', 'electrical', 'electrical', 'diesel', 'electrical', 'electrical',
'electrical', 'electrical', 'electrical']
```

Running the simulation

```
[825]: VMAX = 120/3.6
       N = 2000
       IAT = 13
       env = simpy.Environment()
       rec = SimpleRecorder(env, 0, 3000, 1)
       random.seed(42)
       vehicle_choice = [chooseVehicle([electrical, diesel]) for i in range(2000)]
       iat = [random.uniform(IAT/10, IAT+10) for i in range(N)]
       l = Lane(3000, VMAX)
       r = l.widenRight()

       t0 = 0
       for i in range(N):
           CYCLES = random.randint(4, 8)
           times = randomIntervals(CYCLES)
           speed = [freeMotorwaySpeed()/3.6 for i in range(N)]   #Using the free␣
        ↪motorway speed function to generate the speeds
```

```
    vehicle_choice = chooseVehicle([electrical, diesel])

    if vehicle_choice == electrical:
        a_min_el = -5
        a_max_el = 8
        v = Vehicle(env, rec, startingLane = 1, t0=t0, dx0=speed[-1], t=times,␣
 ↪v=speed, a_min = a_min_el, a_max = a_max_el)
    elif vehicle_choice == diesel:
        a_min_d = -4
        a_max_d = 2.5
        v = Vehicle(env, rec, startingLane = lane_choice, t0=t0, dx0=speed[-1],␣
 ↪t=times, v=speed, a_min = a_min_d, a_max = a_max_el)
    v.traceOvertake = True
#     v.traceSurround = True
rec.run()
```

```
t=   47.0s Overtaking v3 returns to slow lane at x=   30.0m
t=   91.0s Overtaking v6 returns to slow lane at x=    8.3m
t=  109.0s Overtaking v4 overtakes v3 at x=1,715.5m
t=  130.0s Overtaking v9 returns to slow lane at x=   16.1m
t=  138.0s Overtaking v4 returns to slow lane at x=2,725.5m
t=  153.0s Overtaking v9 overtakes v8 at x=  842.5m
t=  179.0s Overtaking v9 returns to slow lane at x=1,829.6m
t=  190.0s Overtaking v12 returns to slow lane at x=   28.9m
t=  212.0s Overtaking v14 returns to slow lane at x=    1.1m
t=  251.0s Overtaking v18 returns to slow lane at x=   20.0m
t=  261.0s Overtaking v18 overtakes v17 at x=  301.6m
t=  278.0s Overtaking v20 overtakes v19 at x=   28.2m
t=  281.0s Overtaking v18 returns to slow lane at x=  907.6m
t=  285.0s Overtaking v18 overtakes v17 at x=1,029.9m
t=  294.0s Overtaking v17 overtakes v16 at x=1,419.2m
t=  297.0s Overtaking v18 returns to slow lane at x=1,435.7m
t=  299.0s Overtaking v20 returns to slow lane at x=  688.4m
t=  342.0s Overtaking v17 returns to slow lane at x=2,954.6m
t=  343.0s Overtaking v23 overtakes v22 at x=  914.4m
t=  373.0s Overtaking v23 returns to slow lane at x=2,043.0m
t=  373.0s Overtaking v27 returns to slow lane at x=   24.8m
t=  386.0s Overtaking v23 overtakes v21 at x=2,564.1m
t=  438.0s Overtaking v33 returns to slow lane at x=   19.4m
t=  443.0s Overtaking v30 overtakes v29 at x=1,590.4m
t=  483.0s Overtaking v38 overtakes v37 at x=    0.6m
t=  493.0s Overtaking v33 overtakes v32 at x=1,923.7m
t=  508.0s Overtaking v38 returns to slow lane at x=1,117.8m
t=  522.0s Overtaking v34 overtakes v32 at x=2,712.6m
t=  526.0s Overtaking v34 returns to slow lane at x=2,857.8m
t=  558.0s Overtaking v40 overtakes v39 at x=1,983.2m
t=  606.0s Overtaking v44 overtakes v43 at x=  997.9m
```

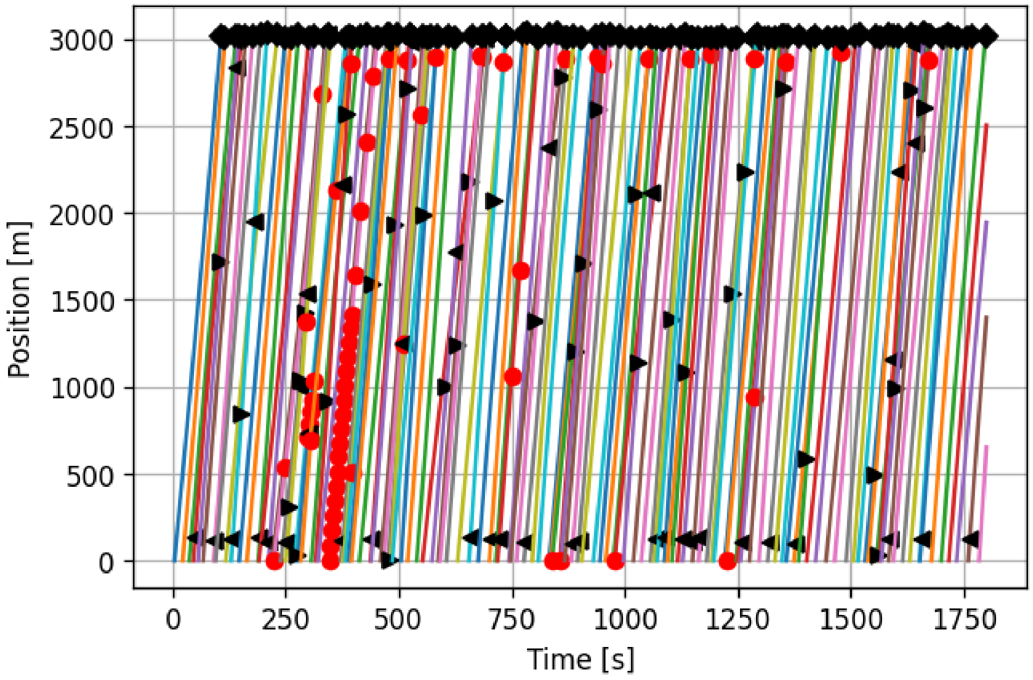
```
t=  625.0s Overtaking v44 returns to slow lane at x=1,659.9m
t=  633.0s Overtaking v46 overtakes v45 at x=1,234.0m
t=  656.0s Overtaking v49 returns to slow lane at x=   18.1m
t=  661.0s Overtaking v45 overtakes v43 at x=2,179.5m
t=  685.0s Overtaking v46 returns to slow lane at x=2,994.0m
t=  688.0s Overtaking v45 returns to slow lane at x=2,948.3m
t=  701.0s Overtaking v51 returns to slow lane at x=   11.8m
t=  711.0s Overtaking v49 overtakes v48 at x=2,064.8m
t=  720.0s Overtaking v53 returns to slow lane at x=   23.4m
t=  778.0s Overtaking v57 returns to slow lane at x=   24.7m
t=  804.0s Overtaking v56 overtakes v55 at x=1,374.0m
t=  829.0s Overtaking v56 returns to slow lane at x=2,257.7m
t=  866.0s Overtaking v57 overtakes v55 at x=2,778.6m
t=  882.0s Overtaking v66 returns to slow lane at x=    9.1m
t=  892.0s Overtaking v63 overtakes v62 at x=1,198.9m
t=  896.0s Overtaking v67 returns to slow lane at x=   20.8m
t=  911.0s Overtaking v64 overtakes v62 at x=1,709.5m
t=  944.0s Overtaking v65 overtakes v62 at x=2,595.5m
t=  947.0s Overtaking v64 returns to slow lane at x=2,972.3m
t=  955.0s Overtaking v65 returns to slow lane at x=2,984.6m
t=1,028.0s Overtaking v71 overtakes v70 at x=2,099.7m
t=1,030.0s Overtaking v74 overtakes v73 at x=1,134.8m
t=1,055.0s Overtaking v74 returns to slow lane at x=2,004.9m
t=1,066.0s Overtaking v78 returns to slow lane at x=   27.6m
t=1,088.0s Overtaking v80 returns to slow lane at x=   14.8m
t=1,105.0s Overtaking v78 overtakes v77 at x=1,385.0m
t=1,129.0s Overtaking v84 returns to slow lane at x=   29.2m
t=1,136.0s Overtaking v82 overtakes v81 at x=1,075.9m
t=1,150.0s Overtaking v85 returns to slow lane at x=    1.9m
t=1,164.0s Overtaking v86 returns to slow lane at x=   13.7m
t=1,241.0s Overtaking v88 overtakes v87 at x=1,533.1m
t=1,257.0s Overtaking v94 returns to slow lane at x=   21.9m
t=1,268.0s Overtaking v89 overtakes v87 at x=2,235.9m
t=1,282.0s Overtaking v88 returns to slow lane at x=2,876.8m
t=1,290.0s Overtaking v89 returns to slow lane at x=2,969.4m
t=1,317.0s Overtaking v97 returns to slow lane at x=   18.6m
t=1,352.0s Overtaking v95 overtakes v94 at x=2,713.7m
t=1,360.0s Overtaking v95 returns to slow lane at x=2,992.4m
t=1,375.0s Overtaking v101 returns to slow lane at x=   15.1m
t=1,403.0s Overtaking v102 overtakes v101 at x=  578.3m
t=1,555.0s Overtaking v111 overtakes v110 at x=  491.9m
t=1,564.0s Overtaking v113 overtakes v112 at x=   28.2m
t=1,585.0s Overtaking v115 returns to slow lane at x=   30.0m
t=1,592.0s Overtaking v113 returns to slow lane at x=1,042.2m
t=1,601.0s Overtaking v114 overtakes v112 at x=  989.7m
t=1,606.0s Overtaking v111 returns to slow lane at x=2,134.8m
t=1,637.0s Overtaking v113 overtakes v110 at x=2,698.2m
t=1,641.0s Overtaking v113 returns to slow lane at x=2,844.8m
```

```
t=1,641.0s Overtaking v114 returns to slow lane at x=2,297.2m
t=1,654.0s Overtaking v120 returns to slow lane at x=   22.8m
t=1,664.0s Overtaking v115 overtakes v112 at x=2,600.5m
t=1,675.0s Overtaking v115 returns to slow lane at x=2,962.1m
t=1,760.0s Overtaking v125 returns to slow lane at x=   16.5m
```

[826]:
```python
df = rec.getData()
df.head()
```

[826]:
```
          t       x          v         a id lane oldLane     pos       event
0  4.024253       0  27.184033         0  0    0    None       0  enter lane
1  5.000000   26.53  27.185800  0.003574  0    0    None   26.53       timer
2  6.000000   53.72  27.191200  0.007237  0    0    None   53.72       timer
3  7.000000   80.92  27.200300    0.0109  0    0    None   80.92       timer
4  8.000000  108.13  27.213000  0.014563  0    0    None  108.13       timer
```

[827]:
```python
rec.plot('t','x')
```



[828]:
```python
travelling_time = Average_tt()
A_tt = sum(travelling_time) / len(travelling_time)
print('Average Travelling Time =', A_tt)
```

```
Average Travelling Time = 97.77690144881927
```

[829]:

```
Avg_speed_3 = l.totalLength()/A_tt
print('Average Speed', Avg_speed_3, 'm/s')
```

```
Average Speed 30.68209316870541 m/s
```

[830]:

```
Throughput = throughput()
print('Throughput in cars/hours = ', Throughput)
```

```
Throughput in cars/hours =  261.8568894145476
```

[831]:

```
Traffic_density = Throughput/Avg_speed_1
print('Traffic Density = ', Traffic_density)
```

```
Traffic Density =  7.886723470105824
```

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