ENGG1001: Programming for Engineers

> Assignment 3: Road Network Analysis

Due: 1600, 21 May, 2021

Aim

The aim of this assignment is to synthesise your understanding of NumPy `ndarrays` and their associated operators by applying them in an engineering problem, namely the analysis of a road network. Your solutions are to be formally implemented in Python.

Learning Objectives

This assignment supports the following learning objectives, as listed in the Electronic Course Profile:

1 Differentiate and apply program constructs such as variables, selection, iteration and sub-routines.

4 Interpret an engineering problem and design an algorithmic solution to the problem.

6 Apply techniques for program testing and debugging.

7 Apply sound programming techniques to the solution of real world engineering problems.

8 Analyse and visualise engineering data.

The Problem

The population in South East Queensland is projected to almost double, to 5.3 million people, over the next 20 years [1]. As one example of this growth, the population in Greater Springfield, Ipswich, is projected to grow from 36 000 in 2013 to 115 000 in 2036 [2]. This will place additional pressure on road networks which already struggle to deal with peak conditions, as a greater number of people commute from home to work, to the Brisbane Airport, and to leisure destinations such as the Gold and Sunshine Coasts.

A selection of arterial roads connecting Greater Springfield to the Brisbane Airport is shown in Figure 1. These include the Centenary Highway, Western Freeway, Logan Motorway, Pacific Motorway, Gateway Motorway, Ipswich Motorway and Highway, and the Legacy Way, AirportLink and Clem7 Tunnels. A summary of the length, total lane count (i.e. in both directions), and speed limit on these roads is included in Table 1. From these data, the peak-hour capacity, P_c, of each road segment can be calculated [3],

$$P_c = \frac{n_l}{f_{phc}} \left(1000 + 12v\right), \tag{1}$$

where n_l is the number of lanes in the direction of travel, f_{phc} is the peak-hour capacity factor, and v is the speed limit of the road segment. The peak-hour capacity is measured in *passenger-car-equivalent vehicles* (PCEVs)[1] per hour [4]. The peak-hour capacity factor represents the percentage of daily traffic that transits a road segment during peak hours. For this road network, it can be assumed to be 80% (i.e. $f_{phc} = 0.8$)

A connected system of roads can be described as a *network*, in which the junctions or intersections are referred to as *nodes* and the road segments between nodes are called *links*. The flow of traffic on a road network can be analysed, from a mathematical point of view, in a similar manner to the flow of electrons in an electric circuit or the flow of water in a pipe network. Based on Kirchoff's Current Law, which was originally defined in the context of electric circuits, the flow of cars into a node is equal to the flow of cars out of a node,

$$[\,A_i\,]^T \{w\} = \{f\}, \tag{2}$$

where $[\,A_i\,]$ is the *incidence matrix*[2] of the road network, $\{w\}$ is the one-dimensional array of traffic volumes on edge road segment, and $\{f\}$ is the one-dimensional array of external traffic flows at each node (incoming

[1] A private car is considered to be 1 PCEV, a motorbike is 0.75 PCEVs and a truck is 3 PCEVs.
[2] See Module 2, Topic 9 for a discussion of incidence and conductance matrices.

measured as positive, and outgoing as negative). This describes the *conservative* property of the network. Using Ohm's Law, which also has its origins in electric circuits, the flow of cars on a road is defined to be proportional to its conductance,

$$\{w\} = -[C][A_i]\{u\}, \tag{3}$$

in which $[C]$ is the *diagonal* conductance matrix and $\{u\}$ is the traffic *potential* at each node. This potential is analogous to the voltage or pressure in an electric circuit or pipe network, respectively.

The conductance can be interpreted as the inverse of resistance in an electric circuit or the inverse of frictional losses in a pipe network. In this simplified traffic analysis, it can be defined for a particular road segment as,

$$C_s = \frac{v n_l}{80}, \tag{4}$$

however it should be noted that more complex definitions exist, including those which are a function of the traffic volume. Combining Equations 2 and 3 gives,

$$[A_i]^T [C][A_i]\{u\} = \{f\}, \tag{5}$$

which can be used to solve for the nodal potentials using the defined incidence and conductance matrices. From there, Equation 3 can be used to calculate the traffic volume on each road segment. The volume capacity ratio, V_{CR}, can then be calculated for each segment as the ratio of the traffic volume and the (peak hour) capacity of each segment [4]. When V_{CR} reaches 1, the road segment is at 100% capacity.

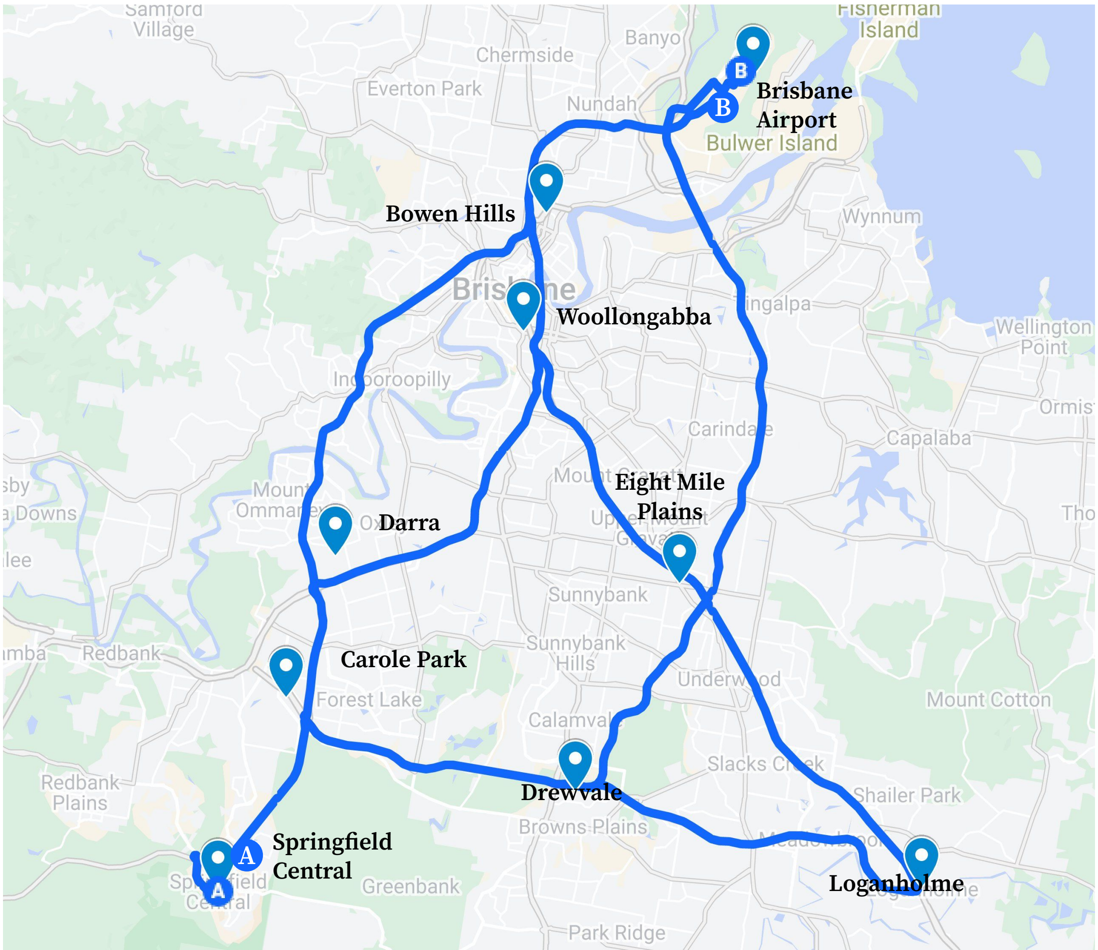

Figure 1: *A selection of arterial roads connecting Greater Springfield to the Brisbane Airport.*

Considering the population growth projections and the current capacity of roads, your objective is to analyse the suitability of the road network shown in Figure 1 for getting commuters **from Greater Springfield to the Brisbane Airport**. Where shortcomings are identified, you are then required to select and analyse investment projects which overcome them. The tasks which support this objective are as follows.

1. The data summarised in Table 1 have been provided in the file, `road_network_data.csv`. Write a function, `network_import()`, to import these data into a dataframe, `network_df`, and add columns for the calculated (peak hour) capacity and conductance of each segment. Note that a `NumPy` array can be added as a column to a dataframe with the following type of command:

   »> df['Column_name']=array_name

   Assign a useful index to the dataframe and then export it to a `.csv` file. The function should return the dataframe, `network_df`, and a `NumPy` array, `locations`, containing the names of all the nodes (eg. 'Darra', 'Logan', etc). All location names should appear in the array only once.

   `network_import()` => `network_df`, `locations` (2 marks)

2. Write a function, `create_adj(*)` to manipulate the imported data and create an adjacency matrix for the road network. (Note that (*) indicates that the function can have whatever input arguments you feel appropriate). Remember that an adjacency matrix would have the unique locations (i.e. nodes) as both row indexes and column indexes. The function should return the adjacency matrix in the form of an array with dimensions, (num_nodes x num_nodes).

   `create_adj(*)` => `adj_arr` (1 mark)

3. Write a function, `create_inc(*)`, to manipulate the imported data and create an incidence matrix for the road network. Remember that an incidence matrix would have the road segments as row indexes and the nodes as column indexes. i.e. it should be an array with dimensions, (num_segments x num_nodes).

   `create_inc(*)` => `inc_arr` (1 mark)

4. Write a function, `create_cond(*)`, to manipulate the imported data and create a conductance matrix for the road network. This matrix should be called `cond_arr` and it should have dimensions, (num_segments x num_segments).

   `create_cond(*)` => `cond_arr` (1 mark)

5. From the 2021 Annual Average Daily Traffic (AADT) count data, the number of *PCEVs* entering the road network at Greater Springfield per hour, T, is 6500.

   Write a function, `calc_flows(entering_traffic,network_df,cond_arr,inc_arr)`. The input arguments are respectively, the external traffic entering Springfield, the dataframe of network data, the conductance array and the incidence array. Assuming that all of the traffic entering at Greater Springfield is destined for the Brisbane Airport (i.e. no vehicles leave at any other node), calculate the *potential* at each node using Eq. 5, the traffic volume in each road segment using Eq. 3, and then the volume capacity ratio for each segment in 2021. Return the potentials in the array, `potentials`, the traffic volume for each road segment in the array `flows` and the volume capacity ratio in the array `vcrs`.

   `calc_flows(entering_traffic,network_df,cond_arr,inc_arr)` => `potentials`, `flows`, `vcrs` (2 marks)

6. Again, assume that the number of *PCEVs* entering the road network at Greater Springfield per hour, T, is 6500. Assume as well that the traffic growth compounds annually according to:

$$T_b = T_a\,(1+G)^{b-a}\,, \tag{6}$$

   where a is the current year, b is a future year, and G is the growth rate.

   Write a function `traffic_proj(first_yr,last_yr,first_traf,growth)`, which calculates and plots the entering traffic volume over the next 10 years, given a projected growth of 10%. The four input arguments are the first year, the last year, the initial traffic volume, and the growth rate. The function should return an array of the years covered and an array of the traffic for those years.

   `traffic_proj(first_yr,last_yr,first_traf,growth)` => `years`, `traffic` (2 marks)

7. Create a new function, `calc_yearsflow(years,traffic,network_df,cond_arr,inc_arr)`, which is a modified version of `calc_flows` written previously. This function calculates the traffic flows for a number of years, rather than for a single year. The input arguments are the years and traffic returned from the `traffic_proj` function, the dataframe of network data, the conductance array and the incidence array, respectively. The function should calculate the *potentials* at each node using Eq. 5, the traffic

volumes in each road segment using Eq. 3, and then the volume capacity ratio for all segments in the years from 2021-2030.

`calc_yearsflow(years,traffic,network_df,cond_arr,inc_arr)` => `potentials`, `flows`, `vcrs` (2 marks)

8. Write a function called `main()` which calls the function developed in the previous item (as well as any other previously written functions) to find the traffic volume and volume capacity ratio for each segment over the 10 year period from 2021.

   `main()` => `adj_arr`, `inc_arr`, `traf_arr`, `con_arr`, `potentials`, `flows`, `vcrs` (2 marks)

   Use your results to identify in which year the first road segment is expected to exceed its capacity. Put your answer as a comment at the end of your a3.py file, with the text: "Year first segment to exceed capacity: xxxx", where xxxx is the answer. (1 marks)

9. You now need to evaluate improvements to the road network. Determine the minimum number of lanes that must be added to the overloaded road segment identified in 8. to keep it under capacity at least until the next road segment fails. Note that the adding of a lane must be accompanied by an additional lane in the opposite direction. Put your answer as a comment at the end of your a3.py file, with the text "Minimum additional lanes: x", where x is the answer. (1 marks)

10. Following the modification proposed in 9., identify the next problem segment in the network and when it will arise. Put your answer as a comment at the end of your a3.py file, with the text "Next problem segment and year of failure: x yyyy", where x is the segment (eg. B) and yyyy is the year of failure. (1 mark)

Table 1: *Summary of the length, total lane count (i.e. in both directions), and speed limit on the arterial roads connecting Greater Springfield to the Brisbane Airport.*

From	**To**	**Length (km)**	**Lanes**	**Speed (km/hr)**
Springfield	Carole Park	7.0	6	80
Carole Park	Darra	5.5	4	100
Carole Park	Drewvale	12.0	6	100
Darra	Wolloongabba	14.0	4	90
Darra	Bowen Hills	19.0	4	80
Drewvale	Loganholme	14.0	6	100
Drewvale	Eight Mile Plains	9.0	4	100
Loganholme	Eight Mile Plains	15.0	6	100
Eight Mile Plains	Woollongabba	12.0	6	100
Woollongabba	Bowen Hills	5.5	6	80
Eight Mile Plains	Brisbane Airport	21.0	6	100
Bowen Hills	Brisbane Airport	9.0	4	80

Marking

Your assignment will be marked on the functionality of the code (13 marks), the short answers about identifying and capacity overloads (3 marks) and for the use of an appropriate coding style (4 marks). A style rubric will be made available on Blackboard.

Submission

You must submit your completed assignment electronically through Blackboard. The only file you submit should be a single Python file called a3.py (use this name, all in lower case). This should be uploaded to Blackboard>Assessment>Assignment 3. You may submit your assignment multiple times before the deadline, as only the last submission will be marked.

Late submission of the assignment will not be accepted. In the event of exceptional personal or medical circumstances that prevent you from handing in the assignment on time, you may submit a request for an extension. See the course profile for details of how to apply for an extension.

Requests for extensions must be made no later than 48 hours prior to the submission deadline. The application and supporting documentation (e.g. medical certificate) must be submitted to the ITEE Coursework Studies office (78-425) or by email to enquiries@itee.uq.edu.au. If submitted electronically, you must retain the original documentation for a minimum period of six months to provide as verification should you be requested to do so.

References

[1] Department of Infrastructure, Local Government and Planning. *ShapingSEQ: South East Queensland Regional Plan 2017,* Brisbane, August 2017, p34.

[2] `https://www.greaterspringfield.com.au/us/key-facts-about-springfield`

[3] US Department of Transport (Federal Highway Administration). *Simplified Highway Capacity Calculation Method for the Highway Performance Monitoring System,* Report No. PL-18-003, October 2017.

[4] Australian Government Department of Transport and Main Roads. *Cost-Benefit Analysis Manual: First Edition,* 2011.