Using Dynamic Time Warping to Improve Efficiency in the Testing, Evaluation, and Validation Phases in Systems Engineering

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Outline

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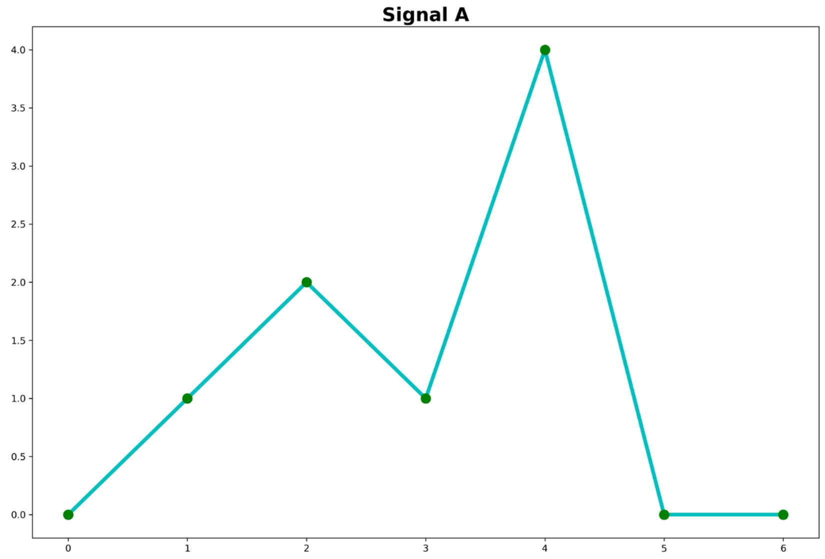
- Prior Work
- Proposal
- Impact on Testing and Evaluation Phase: Example

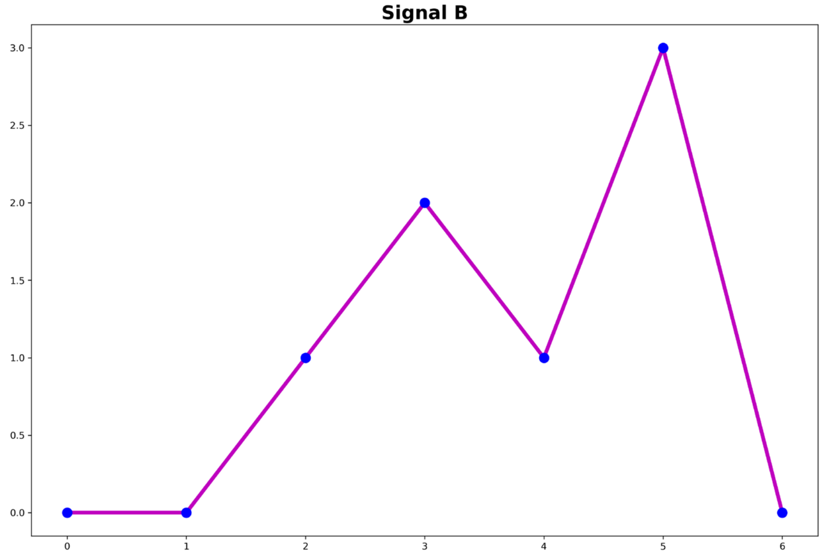
Problem Statement

- Many different activities in automotive industry requiring on-road testing.
  - Each activity (e.g., PEMS, EV range testing) can require numerous iterations to acquire needed data to pass back to development engineers.
  - Each iteration will take X-Y amount of time, with each unit of time costing X-Y amount of dollars for fuel, employee salary, and opportunity cost in waiting for needed data to get back to development engineers.
  - Furthermore, each iteration will vary slightly due to real world variables such as red lights, traffic density, and potential weather condition shifting.
- A method to reduce the number of testing iterations is desired.
  - Development of a nominal cycle derived from X iterations can be used to improve data accuracy, as well as reducing the overall number of iterations required to obtain needed data during Testing and Evaluation.

Algorithm Background

- Dynamic Time Warping (DTW) is an algorithm used to compare the similarity between two time series.
  - Clearly can see Signals A and B are very similar traces, with exception of a slightly different maximum amplitude on Signal A and the 1 second interval placement.

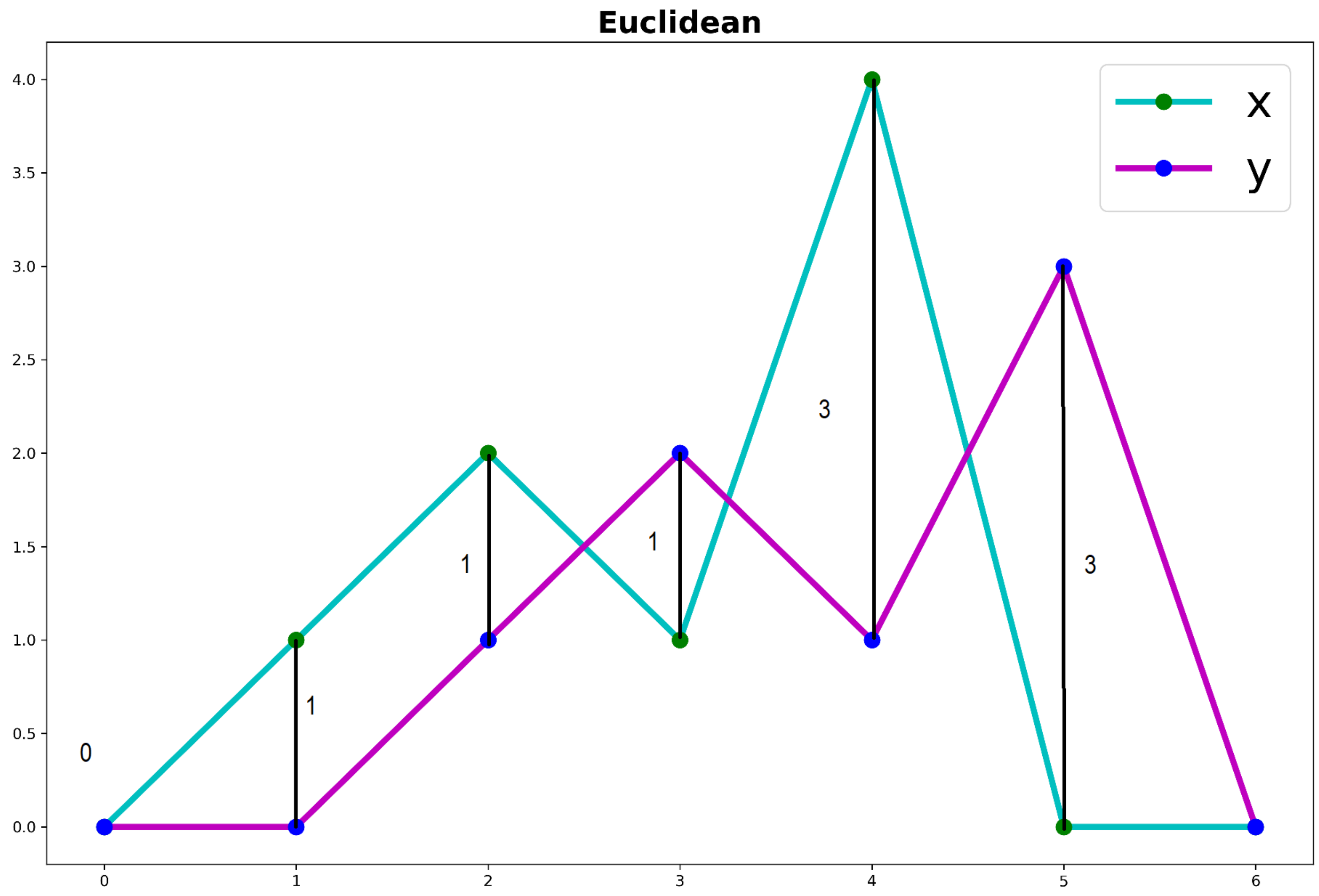




Time

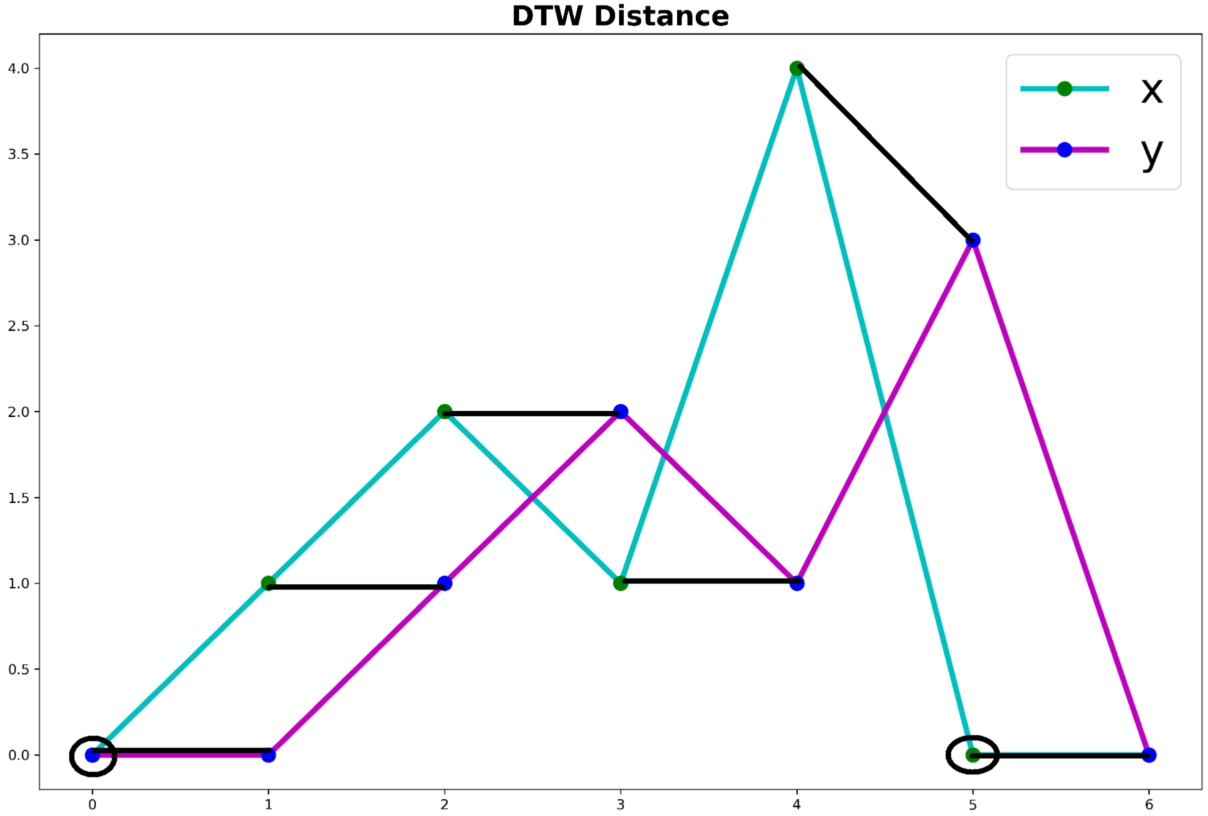
Algorithm Background

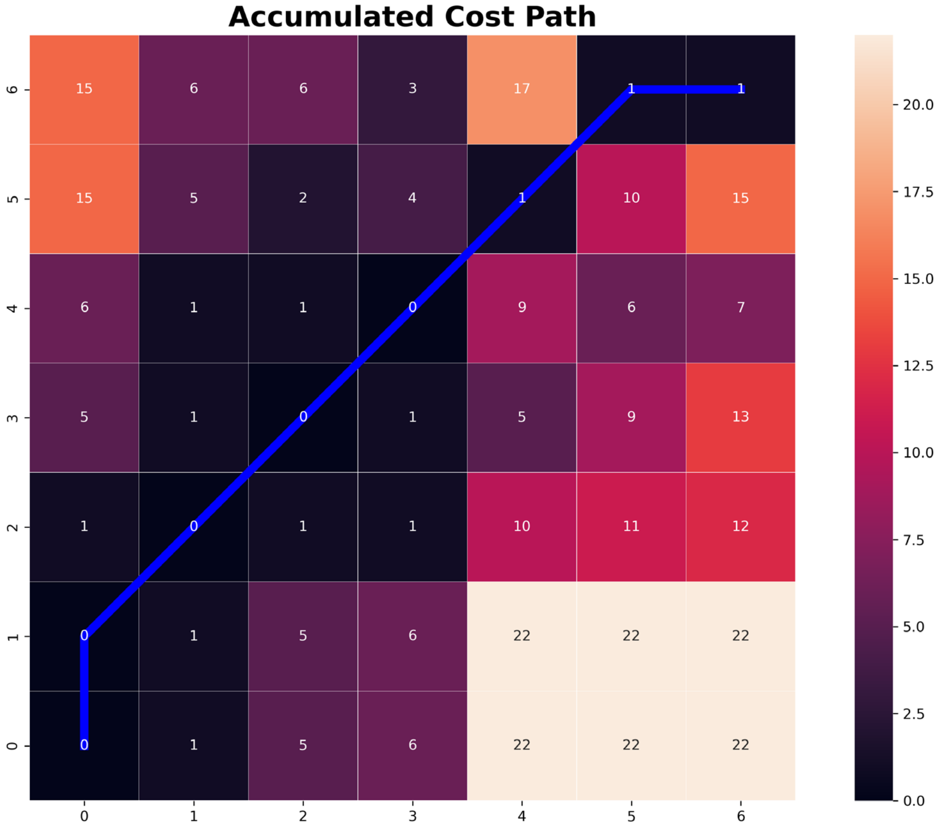
- Euclidean matching
  - Lines up each point with its respective “shared time” point.
  - Adding our accumulated distance scores, we get a Euclidean distance of 0+1+1+1+3+3+0, or 9 total.
  - Depending on scale used, software would determine that these signals are not very similar.



Algorithm Background

- Dynamic Time Warping



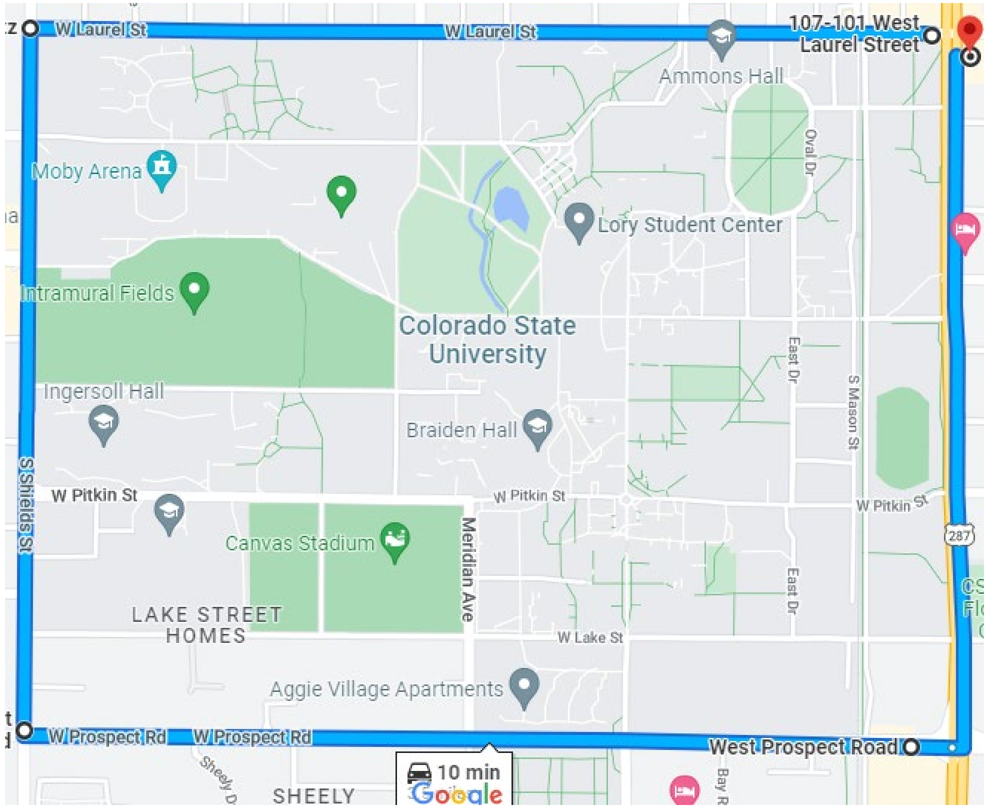


DTW Distance = 1

Usage

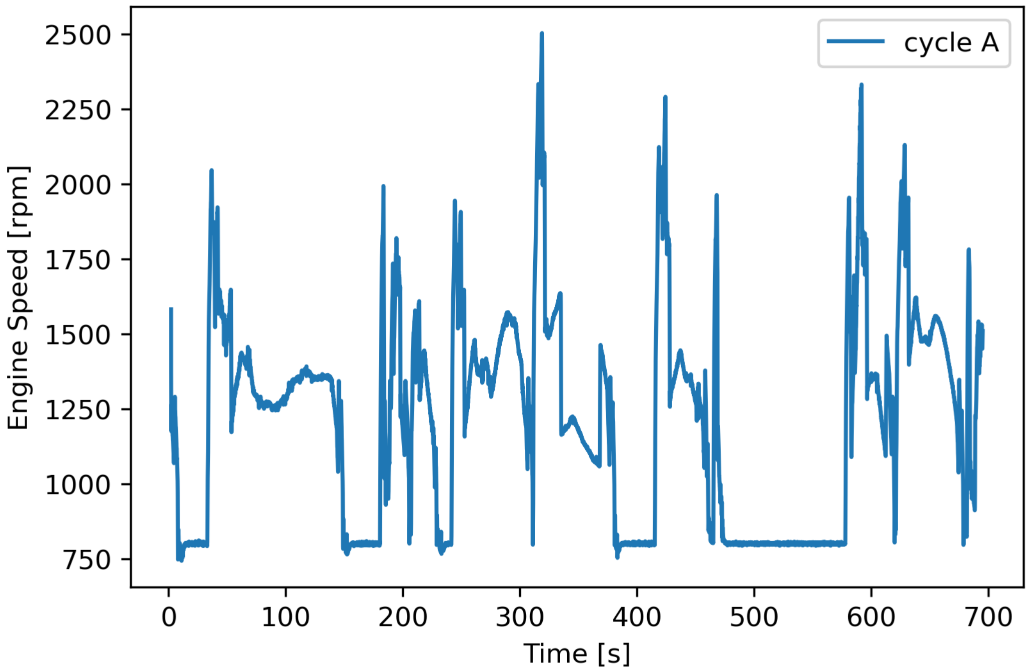
Prior Work

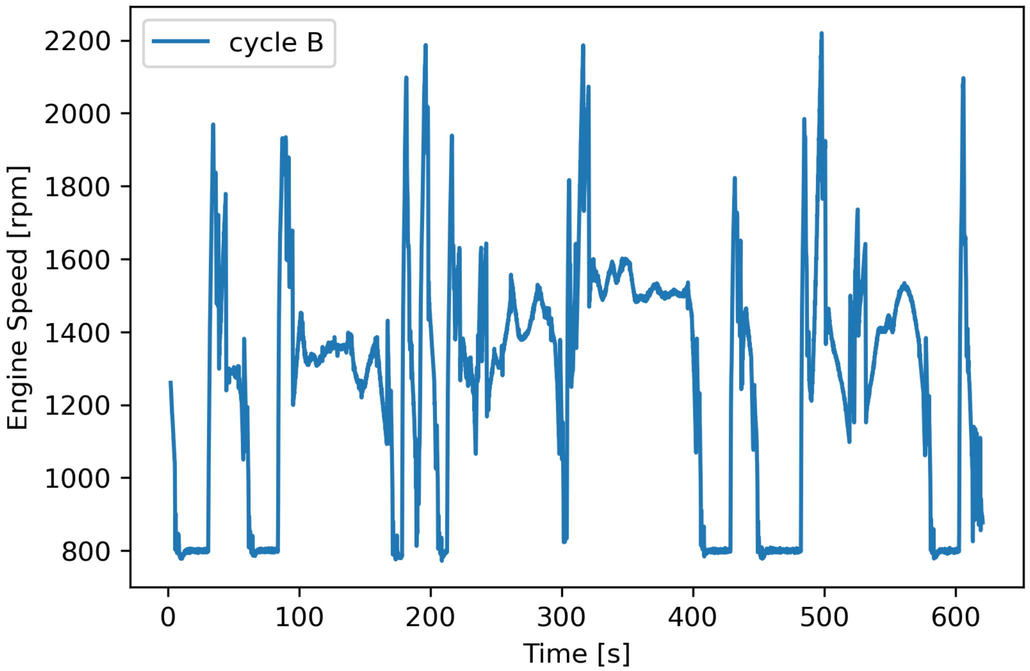
- Work by Lobato et al. [1] shows how DTW can be used to develop a nominal cycle from on-road testing.
  - We took a Kenworth T270 truck and drove it around Colorado State University.
  - CANbus data was recorded and used for comparison (e.g. wheel-based vehicle speed and engine RPM)
  - Each cycle was to take approximately 10 minutes, per Google Maps.
    Actual time was anywhere from 10-15 minutes per cycle due to uncontrollable variables such as traffic density and red lights.



Prior Work

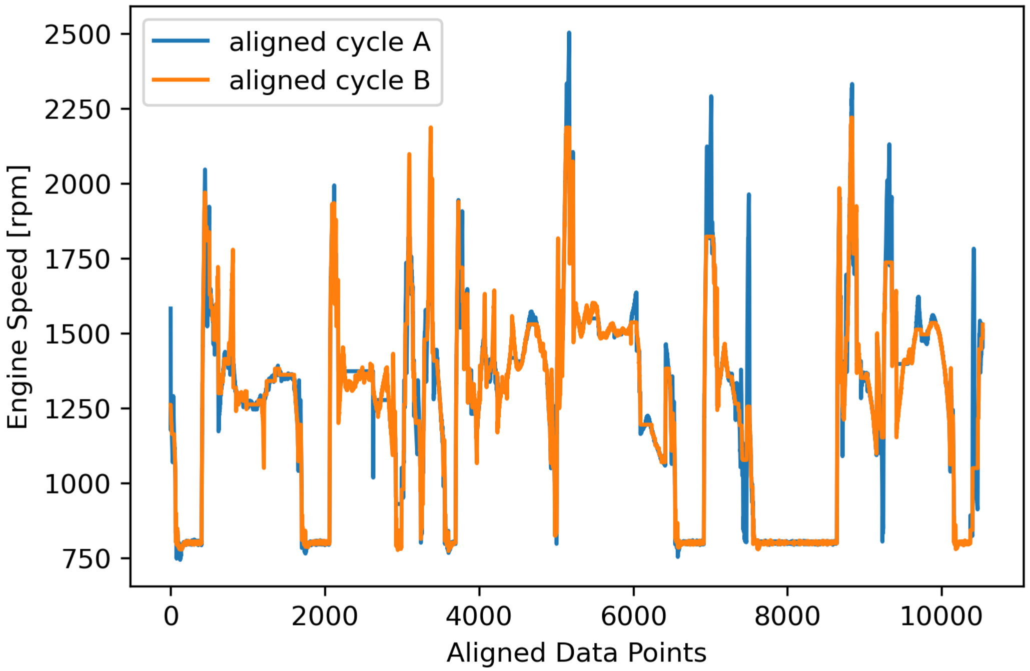
- Two cycles from testing, A and B
  – Similar in overall appearance, but deviations occur. Note the longer idle state in Cycle A, indicating a longer time spent at a stoplight than occurred in Cycle B. Cycle A took a full 70 seconds longer than Cycle B to complete.
  – Euclidean matching gives a distance score of 36132.1

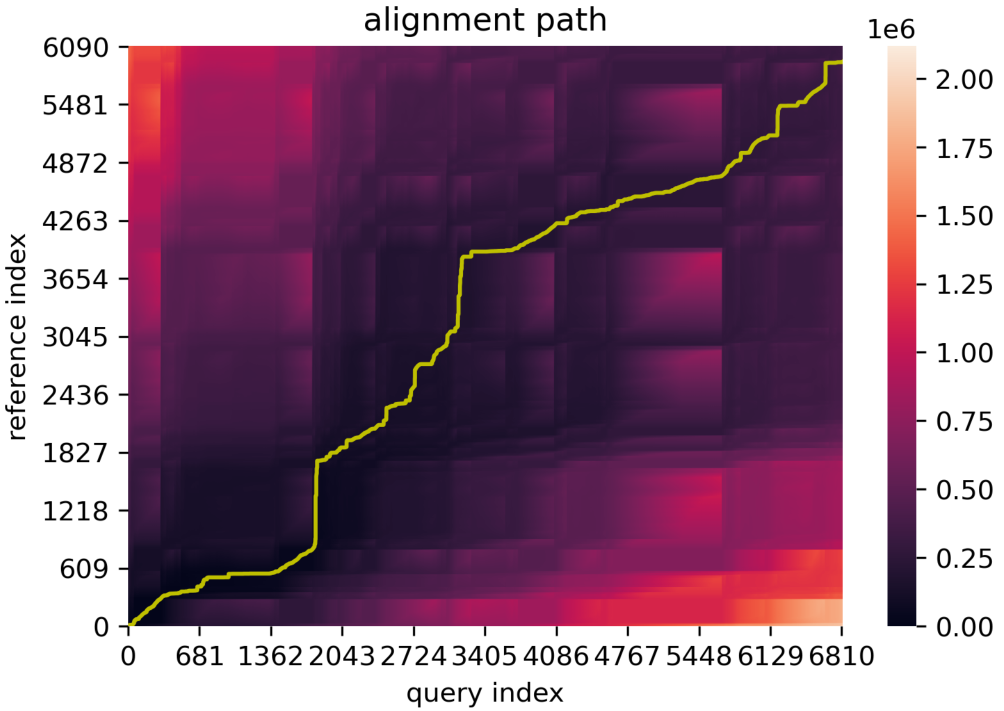




Prior Work

- After DTW is performed, the distance score drops to 7261.69, indicating a considerably closer match than simple Euclidean matching.





Choosing a Nominal Cycle

- Compute DTW between all tests
  - Sum up columns of distance scores, and the lowest sum gives the cycle that is MOST LIKE the other cycles; that is, if you have someone drive the truck on that same cycle, it is likely to be appear most similar to that cycle.

Cycle No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	141076	117946	93788	108957	70515	167316	115560	112344	108531	95558	72674	100296	127550	138301	94856	80345	123555	66112	103675	84372
2	141076	0	110602	128380	128348	87446	139255	174252	111500	120823	122592	118378	141791	132817	113323	130011	117872	116996	156886	102305	173018
3	117946	110602	0	63224	62151	81726	78281	136934	100175	91906	120118	98344	80943	125183	114435	111543	75131	100909	89373	96932	95958
4	93788	128380	63224	0	81869	64421	92296	124609	80382	95762	127099	76429	100922	64132	76184	119180	93749	81145	76624	94276	79983
5	108957	128348	62151	81869	0	90036	80170	104693	115312	118009	92796	72839	93540	139193	66238	72116	115502	102177	83209	84243	85221
6	70515	87446	81726	64421	90036	0	73120	79097	84861	64997	97796	77064	68645	104322	64008	49254	61178	80800	55457	96162	66894
7	167316	139255	78281	92296	80170	73120	0	68616	92699	85965	130231	85336	86360	96291	80339	77054	79644	87522	68790	98340	87843
8	115560	174252	136934	124609	104693	79097	68616	0	96627	117649	74443	107842	105303	137601	70207	79172	86550	94010	90677	99009	113391
9	112344	111500	100175	80382	115312	84861	92699	96627	0	62455	84980	106326	101040	95455	100598	78684	98926	87255	98545	58432	84700
10	108531	120823	91906	95762	118009	64997	85965	117649	62455	0	98355	97693	87141	85698	88026	74087	83971	86661	63280	64964	72309
11	95558	122592	120118	127099	92796	97796	130231	74443	84980	98355	0	106501	135573	124168	91102	88796	108325	82665	110900	93237	91160
12	72674	118378	98344	76429	72839	77064	85336	107842	106326	97693	106501	0	80894	88097	82559	77464	73365	93806	104027	93714	80316
13	100296	141791	80943	100922	93540	68645	86360	105303	101040	87141	135573	80894	0	80843	89974	90088	82511	108273	88361	116394	91692
14	127550	132817	125183	64132	139193	104322	96291	137601	95455	85698	124168	88097	80843	0	108790	81276	91510	82286	101365	89746	115151
15	138301	113323	114435	76184	66238	64008	80339	70207	100598	88026	91102	82559	89974	108790	0	69068	82271	103657	72357	96864	79095
16	94856	130011	111543	119180	72116	49254	77054	79172	78684	74087	88796	77464	90088	81276	69068	0	84449	89307	74962	74073	79893
17	80345	117872	75131	93749	115502	61178	79644	86550	98926	83971	108325	73365	82511	91510	82271	84449	0	81001	68121	83759	67718
18	123555	116996	100909	81145	102177	80800	87522	94010	87255	86661	82665	93806	108273	82286	103657	89307	81001	0	57675	90364	72918
19	66112	156886	89373	76624	83209	55457	68790	90677	98545	63280	110900	104027	88361	101365	72357	74962	68121	57675	0	82088	64050
20	103675	102305	96932	94276	84243	96162	98340	99009	58432	64964	93237	93714	116394	89746	96864	74073	83759	90364	82088	0	71956
21	84372	173018	95958	79983	85221	66894	87843	113391	84700	72309	91160	80316	91692	115151	79095	79893	67718	72918	64050	71956	0
Sum	2123325	**2567471**	1951815	1814453	1896618	**1517799**	1855468	2076242	1851297	1768283	2076395	1793668	1930584	2071475	1787396	1695334	1715899	1822980	1672860	1790535	1757637
Mean	101111	**122270**	92944	86403	90315	**72276**	88356	98869	88157	84204	98876	85413	91933	98642	85114	80730	81709	86809	79660	85264	83697
Rank	20	**21**	16	10	14	**1**	13	18	12	6	19	9	15	17	7	3	4	11	2	8	5

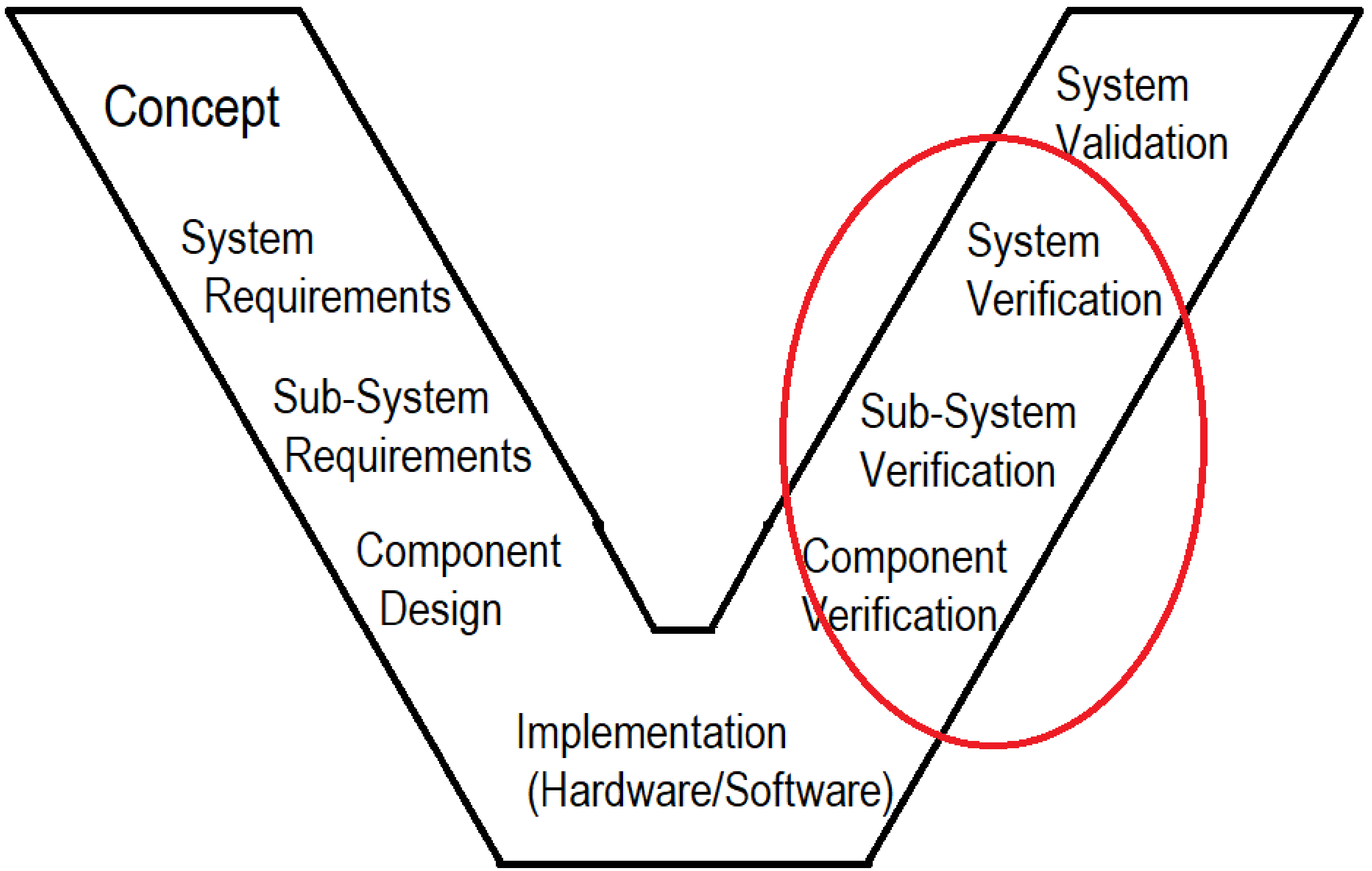
Developing Bounds

- Conversely, we also find the LEAST REPRESENTATIVE cycle.
- Between our MOST and LEAST representative cycles, we develop upper and lower bounds for a given route with a given vehicle at some configuration.
- Our bounds give us a range of values for comparison purposes.
  - Closer to MOST representative cycle indicates a (potentially) positive change, while exceeding it is positive.
  - Closer to LEAST representative cycle indicates a (potentially) negative change, while exceeding it is negative.

Proposal

Testing and Evaluation

- Systems Vee is used to show concurrent design and testing. Shortening time required for testing means getting data back to engineers faster.
- Faster turnarounds lead to a more streamlined development process and making sure to “get it right” in a shorter amount of time prior to final validation.



Proposal

- Use DTW to develop a nominal cycle as previously described.
- Once a nominal cycle is in hand, Development Engineers can make changes based on acquired test data and only need X new cycles as opposed to Y new cycles, due to being able to compare to that nominal cycle.
- Time saved on testing can be substantial, depending on number of tests/cycles required.
- Time saved from repeated Test -> Evaluation -> “Back to the drawing board” can directly lead to reduced development cycles.

Impact on Testing and Evaluation: Example

- EV Range Testing
  - On a full battery charge, drive until the battery is almost depleted.
  - This road test is conducted over a mix of city and freeway driving (usually 60/40).
  - Each cycle takes 30 minutes by distance/speed limits.
  - As shown earlier, uncontrollable variables such as red lights and traffic density can directly impact data from a given cycle. Assume actual duration per cycle 30-40 minutes.
  - So, we:
    - Perform 20 cycles over some given city/highway route.
      - Total time: 10 hours to 13.33 hours
    - Develop upper and lower bounds as detailed previously.

Impact on Testing and Evaluation: Example, continued

- Using accumulated data from this and other testing, the development engineer decides to make some changes in physical vehicle structure and adds in a slightly larger battery to compensate.
- Now, instead of performing the same 20 cycles of road tests above, we:
  - Perform 5 cycles over the same city/highway route.
    - Total time: 2.5 hours to 3.33 hours.
    - Time saving: 7.5 to 10 hours.
  - Compare these values against our developed bounds to see effect of changes.

Potential Applications

- Additional Areas:
  - Autonomous Vehicle Drive Tests
  - AI Sensor Response
- Not limited to time:
  - Can use it for other variables such as Position instead of time

Summary

- DTW is a method to develop nominal cycles for testing.
- Nominal cycles and developed bounds can be used as a reference to compare future cycles to.
- Reduced number of tests required can directly lead to savings in time for testing, time for data to reach engineers for analysis, and overall product development cycle, as well as associated monetary costs.

Questions?

References

- [1]: Lobato, P., Rayno, M., Daily, J., & Bradley, T. (2022). Quantifying repeatability of real-world on-road driving using dynamic time warping. *SAE Technical Paper Series*. https://doi.org/10.4271/2022-01-0269