

# Training Report: Fine-Tuning Facebook Wav2Vec2-Large-960H on Common Voice Dataset

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## 1. Introduction

This report documents the process of fine-tuning the pre-trained `facebook/wav2vec2-large-960h` model using the Common Voice dataset for automatic speech recognition (ASR). The purpose is to improve the accuracy of speech recognition for the dataset while exploring various training strategies.

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## 2. Training Setup

### 2.1 System Info

Dump my system info using command `transformers-cli env` as followoing

- `transformers` version: 4.38.0.dev0
- Platform: Linux-6.8.0-49-generic-x86\_64-with-glibc2.35
- Python version: 3.10.14
- Huggingface\_hub version: 0.21.4
- Safetensors version: 0.4.2
- Accelerate version: 0.27.2
- Accelerate config: not found
- PyTorch version (GPU?): 2.2.1+cu121 (True)
- Tensorflow version (GPU?): not installed (NA)
- Flax version (CPU?/GPU?/TPU?): not installed (NA)
- Jax version: not installed
- JaxLib version: not installed
- Using GPU in script?: **Yes**
- Using distributed or parallel set-up in script?: **parallel**

### My GPU Info:

+-----+-----+-----+									
NVIDIA-SMI 550.120				Driver Version: 550.120				CUDA Version: 12.4	
+-----+-----+-----+									
GPU Name		Persistence-M		Bus-Id		Disp.A		Volatile Uncorr. ECC	
Fan	Temp	Perf	Pwr:Usage/Cap			Memory-Usage		GPU-Util	Compute M.
								MIG M.	
=====									
0	NVIDIA	GeForce RTX 4090	...	Off	00000000:02:00.0		On	N/A	
N/A	41C	P8	7W / 100W			161MiB / 16376MiB		17%	Default
								N/A	
+-----+-----+-----+									
+-----+-----+-----+									
Processes:									
GPU	GI	CI	PID	Type	Process name				GPU Memory
	ID	ID							Usage
=====									
0	N/A	N/A	3413	G	/usr/lib/xorg/Xorg				155MiB
+-----+-----+-----+									

## 2.2 Dataset Description

- **Source:** Common Voice dataset
  - Version: Download from shared zip
  - Language English
- **Audio Files & Text Annotations:** After data processing filter
  - Train dataset length: **136747**
  - Validation dataset length: **58619**

## 2.3 Model Details

- **Pre-trained Model:** facebook/wav2vec2-large-960h
- **Fine-tuning Objective:** CTC (Connectionist Temporal Classification)

## 2.4 Training Configuration

- **Batch Sizes:**
  - Training: 4
  - Evaluation: 4
  - `gradient_accumulation_steps=2` : # Simulates doubling the batch size
- **Learning Rate:**  $2e-5$
- **Number of Epochs:** 3
- **Loss Function:** CTC Loss
- **Optimization:** AdamW optimizer with weight decay 0.01.
- **Precision:** Mixed precision (FP16).
- **Checkpointing:** Models were saved every 500 steps(to change it as dirserd), with a maximum of 2 checkpoints retained.
- **Evaluation:** Validation set evaluated every 100 steps(to change it as dirserd) using Word Error Rate (WER) as the primary metric.
- **freeze encoder** `model.freeze_feature_encoder()`

## 2.5 Training Process

- Model initialization: Pre-trained weights from [facebook/wav2vec2-large-960h](#).

- ### 3. Training Data Processing

### 3.1 Data Preprocessing

- ### 3.2 Dataset Chunks & Caching

**Processed datasets:** were cached in chunks (e.g., 10,000 samples per chunk) to reduce redundant computation and enable efficient reloading during training.

- Training data is split into smaller chunks of size for processing and saving individually.
- Use a generator-based approach instead of apply to avoid creating large intermediate objects. Process and append data to a list in chunks to minimize memory usage.
- Each chunk is cached in a separate directory (part\_1, part\_2, ... etc.) under cache dir.

### 3.3 Load dataset from cache

- Load all cached parts for the train\_dataset, concatenate them into one dataset
- Repeat the above step for the val\_dataset
- **Load dataset:**

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```
Train dataset length: 136747
Validation dataset length: 58619
```

## 4. Training Experiments

### 4.1 Hit Excessive Memory Usage issue

**excessive memory usage** encountered when processing the full training datasets, my host has memory(32GB). And here are the fixes as follows:

- Chunk the dataset into smaller chunks of size `train_chunk_size` for processing and saving individually.
- Use a generator-based approach instead of apply to avoid creating large intermediate objects. Process and append data to a list in chunks to minimize memory usage.
- Cache the chunked data into multi-parts
- Load and concatenate them into one dataset before training

### 4.2 Hit WER Rate was 1.0

The training WER was alway **1.0** caught my eyes at the end of first run of full-dataset training.

#### Steps to Trouble Shooting

1. Debugging and Printing in **compute\_metrics**, to confirm nothing wrong with the code implementation

```
print(f"Sample Prediction[{random_index}]: {pred_str[random_index]}")
print(f"Sample Reference[{random_index}]: {label_str[random_index]}")
```

2. Debugging and Printing for **tokenizer** and **DataCollatorCTCWithPadding**, to confirm nothing wrong with the code

- Printed out the **processor.tokenizer** vocabulary value:

```
{'<pad>': 0, '<s>': 1, '</s>': 2, '<unk>': 3, '|': 4, 'E': 5, 'T': 6,
'A': 7, 'O': 8, 'N': 9, 'I': 10, 'H': 11, 'S': 12, 'R': 13, 'D': 14,
'L': 15, 'U': 16, 'M': 17, 'W': 18, 'C': 19, 'F': 20, 'G': 21, 'Y':
22, 'P': 23, 'B': 24, 'V': 25, 'K': 26, '"': 27, 'X': 28, 'J': 29,
'Q': 30, 'Z': 31}
```

3. Isolate the issueu seems from processed Dataset

Further **Exam the Dataset** and print out a Sample as following:

```
Sample Text: `an army is coming the boy said`
Tokenized text: [3, 3, 4, 3, 3, 3, 3, 4, 3, 3, 4, 3, 3, 3, 3, 3, 3,
```

```
4, 3, 3, 3, 4, 3, 3, 3, 4, 3, 3, 3, 3, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100]
```

Decoded text:

#### 4. Identify The Issue

- Exam the printing in step 3 above, the **Tokenized text**, all characters were encoded to 3("unk") and 4(white space)
- **Root cause:** Somehow, I accidentally converted the text to lower case in **normalize\_text**, however, the model is expected in upper case printed out in the **vocabulary** above:

```
def normalize_text(batch):
    batch["text"] = re.sub(chars_to_ignore_regex, '',
batch["text"]).lower().strip()
    return batch
```

5. The **Fixes**, change the line to **upper case** and the correct value shows out as following:

```
Sample Text: `AN ARMY IS COMING THE BOY SAID`
Tokenized text: [7, 9, 4, 7, 13, 17, 22, 4, 10, 12, 4, 19, 8, 17, 10,
9, 21, 4, 6, 11, 5, 4, 24, 8, 22, 4, 12, 7, 10, 14, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100, -100, -100, -100, -100, -100, -100, -100, -100, -100, -100,
-100]
```

Decoded text: `AN ARMY IS COMING THE BOY SAID<unk>`

### 4.3 Hit CUDA out of Memory

I encountered a **CUDA Out of Memory (OOM)** issue, which occurs when GPU does not have enough free memory to allocate additional resources for the training step shown as following log.

```
Setting up training arguments...
Initializing Trainer...
Starting training...
0%|                                                                    |
0/102561 [00:00<?, ?it/s]Training started
...

result = tensor1.new_full(new_shape, padding_index)
torch.cuda.OutOfMemoryError: CUDA out of memory. Tried to allocate 4.99
GiB. GPU 0 has a total capacity of 15.70 GiB of which 4.99 GiB is free.
Including non-PyTorch memory, this process has 10.69 GiB memory in use. Of
the allocated memory 8.63 GiB is allocated by PyTorch, and 1.75 GiB is
reserved by PyTorch but unallocated. If reserved but unallocated memory is
large try setting PYTORCH_CUDA_ALLOC_CONF=expandable_segments:True to avoid
fragmentation. See documentation for Memory Management
(https://pytorch.org/docs/stable/notes/cuda.html#environment-variables)
0%|                            | 100/102561 [29:34<505:03:32, 17.75s/it]
```

## Steps to Resolve OOM Error

### 1. Reduce `per_device_train_batch_size`:

The batch size is a major contributor to memory usage. Halve the value in the `TrainingArguments`:

```
per_device_train_batch_size=8,
per_device_eval_batch_size=8,
```

If necessary, reduce further to 4 or even 2.

### 2. Enable Gradient Accumulation:

Use smaller batches and accumulate gradients to simulate a larger effective batch size:

```
gradient_accumulation_steps=2, # Simulates doubling the batch size
```

This splits the batch across multiple forward passes, reducing memory demand.

### 3. Use Mixed Precision Training:

Enable mixed precision training to reduce memory usage:

```
fp16=True,
```

This works well if your GPU supports Tensor Cores (NVIDIA Volta and later).

### 4. Clear GPU Memory:

Ensure no other processes are using GPU memory before training:

- Check running processes:

```
nvidia-smi
```

- Kill unwanted processes:

```
kill -9 <process_id>
```

## 5. Restrict GPU Usage:

Limit the script to specific GPUs with more available memory:

```
CUDA_VISIBLE_DEVICES=1 python training-cv.py
```

## 6. Optimize the Model:

- Use model checkpoints with lower memory requirements.
- Reduce the sequence length if applicable:

```
max_length=256, # Or a smaller value based on your dataset
```

## 7. Set CUDA Environment Variable:

Enable dynamic memory management to prevent fragmentation:

```
export PYTORCH_CUDA_ALLOC_CONF=expandable_segments:True
```

## 8. Use Multi-GPU Training:

Distribute the workload across multiple GPUs if available:

```
CUDA_VISIBLE_DEVICES=0,1 python -m torch.distributed.launch --  
nproc_per_node=2 train-cv.py
```

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# 5. Results

Training the full dataset takes approximately 10 hours on my current setup, which is extremely time-consuming, especially with lower hardware configurations. After encountering Word Error Rate (WER) issues during the initial full-dataset training, I decided to use only 10% (to set `LIMIT_TRAIN_DATASET = True`) of the total dataset for the second training attempt. The results are as follows:

5.1 Metrics

```
***** train metrics *****
epoch                =          3.0
train_loss           =    51.0153
train_runtime        =  1:06:09.07
train_samples        =    13674
train_samples_per_second =    10.335
train_steps_per_second  =     1.292
```

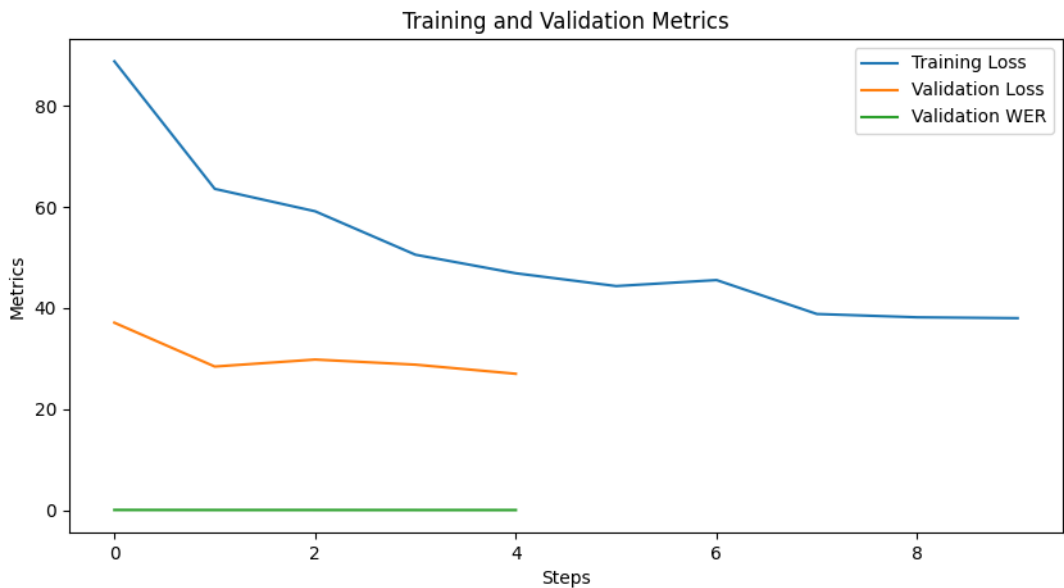
5.2 Training Result

Here is the training result from the logged [training\\_log.csv](#) :

epoch	train_loss	eval_loss	eval_wer
0.292483	88.7678	None	None
0.584966	63.5604	None	None
0.584966	None	37.10172653198242	0.08617345031945754
0.877450	59.1292	None	None
1.169933	50.5406	None	None
1.169933	None	28.435426712036133	0.07506807382227838
1.462416	46.8760	None	None
1.754899	44.3462	None	None
1.754899	None	29.818138122558594	0.07423161116944597
2.047382	45.5298	None	None
2.339865	38.8243	None	None
2.339865	None	28.807701110839844	0.06930182064105074
2.632349	38.1703	None	None
2.924832	38.0019	None	None
2.924832	None	27.004287719726562	0.06588478171884177
2.999123	None	None	None



- And the result plot is as follows:



### 5.3 Observations

**Training Loss:**

- **Trend:** The training loss decreases consistently over the epochs, starting from **88.77** and reducing to **38.00** by epoch 2.92.
  - **Observation:** This suggests that the model is learning and improving its ability to fit the training data as the epochs progress.
- 

**Validation Loss:**

- **Trend:** The validation loss also decreases over time, starting from **37.10** in the first evaluation (epoch 0.58) to **27.00** in the final evaluation (epoch 2.92).
  - **Observation:** This indicates that the model's performance on unseen data is improving over time.
- 

**Word Error Rate (WER):**

- **Trend:** The WER shows a steady decline, starting from **0.0861** (8.61%) at epoch 0.58 to **0.0658** (6.58%) at epoch 2.92.
  - **Observation:** This is a clear indication that the model is becoming better at predicting and aligning text outputs with the expected ground truth over time.
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## 6. Summary and Recommendations

### 6.1 Summary

- **Consistent Improvement:** The training loss, validation loss, and WER all show a decreasing trend, reflecting effective model training and validation.

- **No Overfitting:** There is no evidence of overfitting since both training and validation metrics are improving.
- **Performance:** The declining WER highlights that the model's transcription accuracy is progressively improving.

## 6.2 Recommendations for Improvement

### Recommendations for Improvement

Here are actionable recommendations to further enhance the model's performance based on the training results:

#### 1. Data Augmentation:

- **Techniques:** Introduce variations in the input data such as speed perturbation, volume scaling, or noise injection to improve the model's robustness.
- **Impact:** This can help the model generalize better, especially in diverse real-world scenarios.

#### 2. Hyperparameter Tuning:

- **Learning Rate:** Experiment with different learning rate schedules like cosine annealing or cyclic learning rates to achieve more stable convergence.
- **Batch Size:** Test larger batch sizes to improve gradient estimates or smaller batch sizes for finer updates, depending on hardware constraints.
- **Warmup Steps:** Adjust the number of warmup steps to balance between fast convergence and stability.

#### 3. Model Architecture:

- **Transformer-based Models:** Fine-tune transformer-based architectures (e.g., Wav2Vec 2.0 or HuBERT) for potential performance gains in WER.
- **Language Models:** Incorporate external language models for post-processing predictions, improving contextual understanding.

#### 4. Additional Pre-Training:

- **Domain-Specific Data:** Use unannotated domain-specific audio for pre-training before fine-tuning. This can help the model adapt better to specific use cases.
- **Multilingual Training:** If applicable, include diverse datasets to improve cross-linguistic generalization.

#### 5. Regularization:

- **Dropout:** Apply dropout layers to prevent overfitting, especially as the training and validation losses approach similar values.
- **Label Smoothing:** Introduce label smoothing to make the model more tolerant of uncertainty in predictions.
- **Weight Decay:** Regularize weights to prevent excessively large updates.

#### 6. Evaluation and Metrics:

- **Fine-Grained Evaluation:** Analyze WER on subsets of data (e.g., noisy vs. clean audio, different speakers) to identify specific areas for improvement.
- **Validation Strategy:** Increase the frequency of validation during training to monitor overfitting trends more closely.

#### 7. Training Data Optimization:

- **Balanced Sampling:** Ensure an even representation of different classes or speaker accents in the dataset.
- **Data Pruning:** Remove or fix low-quality samples that could negatively affect model training.

#### 8. Longer Training Duration:

- Extend the training to more epochs or iterations, leveraging early stopping to determine the optimal stopping point for model performance.

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## 7. Conclusion

The training process demonstrated effectiveness, evidenced by the steady decline in both training and validation losses across epochs. The alignment of the decreasing validation loss with the training loss suggests an absence of immediate overfitting, indicating the model's ability to generalize well to unseen data. Furthermore, the consistent improvement in Word Error Rate (WER) reinforces the model's progress in learning and achieving better speech recognition accuracy.

This experiment establishes a strong foundation for further advancements in training speech recognition models on the Common Voice dataset. Future iterations will prioritize implementing the recommended strategies, such as data augmentation, hyperparameter tuning, and leveraging advanced model architectures, to refine and enhance performance.

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## 8. References

- Common Voice Dataset Documentation
- Transformers Library Documentation
- [Fine-tuning Wav2Vec2 for English ASR](#).